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TURBULENT BOUNDARY LAYER SEPARATION CHARACTERISTICS WITH BLOWING IN AN OSCILLATING FLOW

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Turbulent Boundary Layer Separation Characteristics

with Blowing in an Oscillating Flow

by

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The Naval Postgraduate School open circuit oscillating flow wind tunnel was used to study the blowing requirements to maintain an attached turbulent boundary layer in an oscillating freestream flow with an adverse pressure gradient. Boundary layer separation was visualized through the use of tufts. Freestream flow oscillation frequency was found to have an effect on the flowing required to maintain attached flow. This frequency dependence exhibits characteristics which suggest resonant behavior.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

b	Width of the blowing slot, feet
C_D	Drag coefficient
C_L	Lift coefficient
C_m	Moment coefficient
C_p	Pressure coefficient, $(P-P_\infty)/q$
C_{p_x}	C_p derivative with respect to x position along plate
C_Q	Volumetric coefficient of blown air, as defined in Equation II-1
C_μ	Momentum coefficient of blown air, as defined in Equation II-2
C_{μ_R}	Blowing coefficient required to maintain attached flow
h	Height of the blowing slot, feet
ℓ	Slant length of the diffuser section, feet
$\dot{m}_j$	Mass flow of blown air, slugs per second
P_E	Pressure at exit section of diffuser, pounds per square foot
P_o	Total pressure inside blown air supply duct, pounds per square foot
P_∞	Freestream static pressure, pounds per square foot
Q_j	Volume flow of blown air, cubic feet per second
q_∞	Freestream dynamic pressure, pounds per square foot
R_h	Slot height Reynolds number, $V_j h/\nu$
R_ℓ	Reynolds number, $U_\infty \ell/\nu$
S	Characteristic area of interest, area of blown wall of diffuser section for this study, square feet
T_o	Total temperature inside blown air supply duct, degrees Rankine
T_∞	Freestream temperature, degrees Rankine

U_E	Velocity at exit section of diffuser, feet per second
U_∞	Freestream mean velocity, feet per second
V_j	Jet velocity of blown air assuming isentropic expansion from P_o and T_o to P and T, feet per second
V_{jR}	Minimum jet velocity that will just prevent separation, feet per second
x	Slant distance along diffuser wall measured from inlet section, feet
ΔP_E	$(P_E - P_\infty)$, the pressure rise through the diffuser, pounds per square foot
ΔU_∞	Amplitude of perturbation in velocity at inlet to the diffuser, feet per second
δ	Displacement thickness of boundary layer at exit section, feet
μ	Absolute viscosity, slugs per foot-second
ν	Kinematic viscosity, feet squared per second
ρ	Density, slugs per cubic foot
ω	Frequency of oscillation, radians per second

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Grateful acknowledgement is also due Dr. James A. Miller for his initial helpful suggestions, and to Dr. T. H. Gawain for his help in developing parts of the analysis.

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I. INTRODUCTION

The study of viscous unsteady flows have become increasingly important in recent years. Typical examples of unsteady flows are found in helicopter blade aerodynamics and in gas turbine engine internal flows. The development of advanced design concepts in helicopters, ships, and propulsion systems requires a basic understanding of the nature of unsteady flows. The complexity of the problem does not lend itself readily to either analytic or experimental study, even when limited to flow with laminar boundary layers. Furthermore, most of the problems of interest are characterized by turbulence and turbulent boundary layers, which greatly increases the difficulty of the study. Regardless of the difficulties involved the field is of such importance as to warrant the expenditure of time and effort to widen the understanding of its characteristics.

The present study was to experimentally examine the effect of different levels of blowing on turbulent boundary layer separation in an oscillating freestream. The effects of changes in frequency and magnitude of the freestream oscillation on the blowing requirements to maintain an attached boundary layer were studied.

II. BACKGROUND

A. NON-STEADY FLOWS

1. Analytic Studies

Previous analytic studies have been confined mostly to flows which have a laminar boundary layer. The earliest was Stokes [Ref. 1] study of the doubly infinite flat plate oscillating in its own plane in a fluid at rest. Rayleigh [Ref. 2] considered the second order effects of this problem. Schlichting [Ref. 3] expanded Rayleigh's work to include the boundary layer assumptions. All of these were simple unsteady flows without a mean flow or pressure gradient. Lighthill [Ref. 4] later treated the case of small magnitude, low frequency, sinusoidal oscillations superimposed on a steady flow about a cylinder and a semi-infinite flat plate. Using small perturbation theory and restricting the solution to first order terms he determined that, at low frequencies the flow is essentially quasi-steady. The unsteady flow had the same characteristics for any instantaneous magnitude of freestream velocity as a steady flow of the same velocity. As frequency is increased a limiting frequency is reached beyond which the boundary layer reacts as it would without a mean flow. Lin [Ref. 5] analyzed the high frequency case for large amplitude oscillations. He found that the governing equations became essentially linear at high frequencies allowing separation of oscillatory and steady components. Nickerson [Ref. 6] expanded this

work to include higher order perturbation terms. Barriol and Lucius [Ref. 7] used numerical methods to obtain asymptotic solutions to the boundary layer equations for oscillating flow on a semi-infinite flat plate with no pressure gradient. Their solution agrees with those of Lighthill and Nickerson.

The previously mentioned studies have all dealt with laminar boundary layer flows. The analytic approach to turbulent boundary layer flow has apparently been less fruitful. Karlssen [Ref. 8] separated the fluctuations into periodic and random components, and by averaging over a complete period obtained equations similar to the steady turbulent boundary layer equations, but with an additional fluctuating term. Other analytic works [Ref. 9, 10] have used linearized solutions to solve the pressure distribution on an airfoil at low angle of attack, but are applicable to only a small number of cases.

2. Experimental Studies

A great deal more work has been done experimentally than analytically, but there are still large gaps in the field. Nickerson [Ref. 6] partially verified both his analysis and that of Lighthill. Miller [Ref. 11] studied the transition phenomena on a flat plate in oscillating flow. He was able to confirm some of the previous analytic predictions. In addition he determined the transition Reynolds number, turbulent Reynolds number, and turbulent intermittency factor for oscillating Blasius type flow. Despard

[Ref. 12] investigated the separation of a laminar boundary layer in oscillating flow. He proposed that the definition of separation for a laminar boundary layer in an oscillating freestream be the initial occurrence of zero velocity or reverse flow at some point in the velocity profile throughout the entire cycle of oscillation. He was also able to make some prediction about the behavior of the separation point.

Morrissey [Ref. 13] investigated the effects of large amplitude flow oscillations on the heat transfer from a flat plate with a turbulent boundary layer. Jacobs [Ref. 14] studied the effect of oscillating mean freestream on the turbulent intensity distribution in a turbulent boundary layer. These two studies indicate that unsteady flows exhibit no significant alteration in the character of the eddy diffusivity or the turbulent intensity distribution when compared to a steady turbulent flow. Banning [Ref. 15] investigated the pressure distribution on an airfoil in a turbulent oscillating freestream. Others have studied the effects of oscillating flows with compressibility effects included.

B. BLOWING TO AVOID SEPARATION

1. Experimental Studies

Boundary layer control through blowing has been with us almost as long as the boundary layer concept itself. The idea arose initially from the use of slots as a lift augmentation device, which was suggested by Lachmann of Germany in

1918 and later tried by him and Handley-Page in England. Betz [Ref. 16] theorized that the effect of the slots was to accelerate the boundary layer. Baumann [Ref. 17] was led by this interpretation to replace the air passing through the slot with air ejected from the wing interior. This produced roughly the same effect as the slots with the added advantage of being able to control the effect by control of the pressure inside the wing.

Until the 1940's little more was done with blowing except some experiments which used it as an alternative for ailerons. This was done by blowing out a slot over a short wing section to induce high lift. By differential blowing on the wing a rolling moment was produced similar to that of an aileron. In 1942-43, triggered, no doubt, by the war, experiments began to be conducted in France, Germany and the United States, followed shortly by Britain. Probably the most important contribution of this era was made in 1948 by Poisson-Quinton [Ref. 18]. Prior to this time the common parameter to measure blowing was

$$C_Q = \frac{Q_j}{U_\infty S} \qquad \text{(II-1)}$$

where Q_j is the volumetric flow through the slot, U_∞ the mean freestream velocity and S the characteristic area of interest. Schwier [Ref. 19] had shown that narrow slots were more efficient than wide ones. Poisson-Quinton verified this and suggested that a more appropriate blowing parameter was

$$C_\mu = \frac{\dot{m}_j V_j}{q_\infty S} \qquad \text{(II-2)}$$

where $\dot{m}_j$ is the mass flow of blown air, V_j the jet velocity at the exit assuming isentropic expansion from the total pressure and temperature inside the jet supply duct, and q_∞ the freestream dynamic pressure. Subsequent experimental work supported the use of this parameter to predict the effectiveness of blowing.

Unfortunately all the early efforts in boundary layer control through blowing were hampered by the great difficulties involved in practical applications. Major obstacles were a supply of high pressure air and the weight penalty associated with the ducting. However, with the advent of gas turbine engines for aircraft propulsion a good supply of air became available. With this development and advances in metal alloys and other lightweight materials of high strength, blowing has become much more attractive. Since 1950 the use of blowing has proceeded at an accelerating pace. Unfortunately little work has been accomplished in the area with which this study is concerned. The majority of the work has been in the use of blowing for lift augmentation by delaying stall or by providing circulation control. All of these experiments present results in terms of C_ℓ, C_D, and C_m and their variation with C_μ. Also the values of C_μ required for lift augmentation are much greater than that required to keep the boundary layer from separating under the influence of an adverse pressure gradient. As a result

there has been little interest in studying the amount of blowing required to maintain streamline flow. The only information to be gleaned from this work was that higher pressure gradients require higher C_μ to overcome separation.

2. Analytic Studies

Theoretically, most of the interest lies in increasing lift, rather than detailed study of blowing requirements to maintain attachment. There are, however, a few notable exceptions. Carriere and Eichelbrenner [Ref. 23] developed a method for calculating the conditions for flow re-attachment by a jet discharging against adverse pressure gradient. Their analysis, unfortunately, was heavily dependent on the availability of empirical profiles from experimentation and several arbitrary assumptions. Within these limits it did, however, provide solution to cases with weak pressure gradients. Kozlous and Zyanyak [Ref. 24] have recently analyzed a laminar boundary layer in an unsteady incoming motion around a body of arbitrary shape with either suction or blowing. They used a six degree polynomial to describe the boundary layer under these conditions. Their result was an integral equation which could be integrated directly, or reduced to a quadrature, depending on the velocity profile. They were able to verify their analysis for a symmetric wing in a start-up situation. This can be extended to an oscillating flow by varying the description of the incoming motion. Although derived for lift and drag predictions in laminar flows with blowing, this analysis shows great promise

for being extended to turbulent boundary layer blowing requirement predictions. The greatest difficulty with this extension, or any prediction of blowing in turbulent regimes, is that much of the energy imparted to the boundary layer is by turbulent mixing which defies accurate modeling.

C. APPLICATIONS

Recently there has been work accomplished toward the application of boundary layer control in an oscillating flow. Englar and Williams [Ref. 12, 23, 24] have applied boundary layer energization through blowing to augment the lift of a submarine stern plane and a symmetric airfoil at angle of attack. They have also applied tangential blowing to the blades of a helicopter rotor system (the circulation control rotor) with encouraging results.

There has not, however, been any detailed studies of the actual flow over the surface and its behavior under the conditions of high angle of attack, large pressure gradient, turbulence, oscillating freestream, or blowing to energize the boundary layer. The prediction of blowing requirements under these conditions will for the foreseeable future, rely heavily on empirical methods based upon experimental results. The present study is an attempt to provide some of this experimental data.

III. DESCRIPTION OF APPARATUS

A. OSCILLATING FLOW WIND TUNNEL

1. General Description

The experimental work was conducted in the lowspeed, oscillating flow wind tunnel located in the Aeronautics Laboratories of the Naval Postgraduate School. This wind tunnel is of open circuit design, with a 24-inch square by 223-inch long test section. A plan view of the tunnel is presented in Figure III.1. The tunnel inlet is eight feet square, resulting in a 16:1 contraction ratio. Three high solidity screens located in the inlet section just upstream of the nozzle produce measured freestream turbulence intensities of 0.261 to 0.413 percent for the velocities encountered in the present work.

The wind tunnel drive consists of two Joy Axivane Fans in series, each of which has an internal, 100 horsepower, direct connected, 1750 rpm motor. The fan blades are internally adjustable through a pitch range of 25 to 55 degrees, providing a wide operating range of test section velocities. Two sets of variable inlet vanes, located immediately upstream of each fan, are externally operated to provide control of test section velocity. These vanes are of multileaf design, and preswirl the air in the direction of fan rotation to reduce fan capacity. The total range of tunnel velocity is from 10 to 250 ft. per second.

2. Rotating Shutter Valve

Two fundamental methods of creating an oscillating flow environment have been employed in the past. Nickerson [Ref. 6] introduced oscillations by oscillating the model in a steady flow environment. This method severely restricts the range of attainable frequencies because of mechanical complications, and also introduces measurement difficulties. The other method is to actually oscillate the flow over a stationary model. Hill [Ref. 25] used a sliding shutter to impose oscillations on the freestream but was restricted by mechanical limitations to low frequencies.

The most successful method of obtaining an oscillating flow with large ranges of frequency and amplitude was that employed by Karlssen [Ref. 8] and later by Miller [Ref. 11] in his investigation of transition phenomena. A rotating shutter valve, immediately downstream of the test section, is employed to superimpose a periodic variation of velocity on the mean flow. The method used in the present investigation is identical to that employed by Miller. The shutter valve consists of four horizontal steel shafts equally spaced across the test section. The shafts are slotted to accommodate flat blades of various widths, forming a set of four butterfly valves spanning the test section. Figure III.2 is a photograph of the shutter valve. Each blade is driven from its immediate neighbor by means of a timing belt and pulley arrangement. The bottom shaft is driven by a five horsepower, variable speed, electric motor, through a timing belt

and pulley. An intermediate shaft between the motor and shutter valve permits a wide variety of pulley ratios. This drive arrangement provides a frequency range from 0.4 cycles per second to the first critical frequency of 933 cycles per second. The electric motor presently in use, however, restricts the oscillation frequency to a maximum of 240 cycles per second. The amplitude of oscillation is controlled by blade width. Test section closure may be varied from 25 to 100 percent. The resulting amplitude of oscillation of test section velocity is a function of frequency, mean velocity, and pressure gradient. In this investigation blades producing 83.3 percent closure were used resulting in a perturbation range from 5 to 25 percent of the local mean freestream velocity. Figure III.3 is a picture of the shutter valve drive arrangement.

3. Test Section

The wind tunnel test section is shown in Figure III.4. Continuous pieces of two-inch thick aluminum, 24 inches wide and 223 inches long, form the upper and lower test section walls. Each of the sidewalls consists of three two-inch thick panels of stress relieved lucite. For this investigation the central sidewall panel on the opposite side of the tunnel from the control console was replaced with two-inch thick plywood to facilitate the mounting of instrumentation and access to the model plenum. The Lucite panels on the console side of the test section are hinged and may be raised hydraulically, providing access to the test section.

Figure III.5 shows the test section with the door open. The heavy construction of the test section is intended to minimize deflections induced by rapid changes in static pressure.

Previous test on the test section velocity profile have shown the velocity variation is less than one percent of mean to within three inches of the wall [Ref. 12]. Figure III.6 is a photographic view of the test section and control console with the model in place.

B. MODEL

The model used in this investigation consisted of two plugs placed in the test section with a flat plate halfway between them. Each plug had a smoothly curved leading edge, followed by 42-inch straight section, then a diverging section as shown in Fig. III.7. The maximum thickness of each plug was six inches and the plate was ½ inch leaving 5-3/4 inches between each plug and the plate. The diverging section departs from the horizontal by 27°. The slart length was 13 inches and the characteristic area chosen for calculation of blowing coefficient was the plane area of the diverging section which was 305.5 square inches.

Each plug contained a 1700 cubic inch plenum chamber. The entrance to the plenum was a two-inch diameter hole to which the blowing air supply hose was connected. The blowing slots were 23.5 inches wide. The upper slot height was .041 inch and the lower was .055 inch. The difference in slot heights provided information on the blowing coefficient

requirements as a function of slot height. Because of its smaller slot height the upper jet would need less mass flow but higher jet velocity to achieve the same blowing coefficient as the lower slot. Figure III.8 shows the plenum and slot configuration. Blowing air was provided by a Carrier three-stage centrifugal compressor, driven by a 300 horsepower General Electric induction motor. It was capable of supplying 1900 cubic feet per minute at 29.5 psia. Each plenum was supplied and metered independently by a gate valve in the three-inch supply pipe. Each pipe had an orifice plate with a 1.8 inch hole diameter for use in mass flow measurements.

The flat plate, constructed of a slab of phenolic material 24-inches wide, 60-inches long, and ½ inch thick had a rounded leading edge in order to avoid leading edge separation. The last five inches was tapered and hinged. For this study the hinged portion remained at zero angle of incidence with respect to the flat plate. The plate was mounted at the center line of the test section and ran from a point 7.5-inches from the leading edge of the plugs to a point five-inches back to the end of the plugs as shown in Fig. III.7.

Figure III.9 shows a schematic of the test setup.

C. INSTRUMENTATION AND CALIBRATION

1. Freestream Sensors

A conventional pitot static tube located 22.5 inches aft of the model leading edge and midway between the flat plate and the upper model section was used to measure mean

freestream dynamic pressure. A hot wire probe 29.5 inches aft of the model leading edge and midway between the plate and the lower model section was used to determine magnitude of velocity perturbations during oscillations. The probe was connected to a locally manufactured, single channel, hot wire anemometer which was connected to a Tektronix 555 Dual-beam oscilloscope for display and read out. Previous experimentation [Ref. 12] has indicated that the hot wire circuitry is linear with freestream velocity. A short calibration run was made which verified this.

The frequency of oscillation was obtained from a magnetic pickup mounted out-board of the uppermost shutter blade shaft, as seen in Fig. III.2. The output frequency was read on a Dynascience digital counter.

The pressure distribution in the tunnel was measured by a series of flush pressure ports one inch apart in the flat plate. They ran from a point five inches in front of the diverging section of the model to 2.3 inches from the end of the model. The ports were connected to a 40 tube, 250 centimeter upright manometer board. The median reading of the oscillations was the recorded pressure value.

2. Blowing Coefficient

The mass flow of blowing air was measured by a pair of orifice plates in the three inch supply lines. The orifice plates were calibrated *in situ*. This was accomplished by connecting the blower supply lines to a 76.5 cubic feet per minute rotameter manufactured by Fischer and Porter

Company. The pressure drop across the plates was measured by a 36 inch U-tube water manometer. The results of the calibration were plotted against the ASME values as shown in Fig. III.10. The differences were so small as to be negligible, therefore it was deemed reasonable to extrapolate the curve along the same form as the ASME curve to cover values not covered by the rotameter. Figure III.10 was then used to find the volume flow of air for any value of pressure drop.

The pressure downstream of the orifice plate was measured with a 36 inch U-tube mercurcy manometer vented to the atmosphere. Air temperature remained essentially constant from the compressor to the plenums. With the volume flow, pressure and temperature, the mass flow could easily be calculated.

The blowing jet velocity for calculation of C_μ has, historically, been defined as the velocity at the exit assuming isentropic from some pressure and temperature inside the supply duct. These were measured with a special purpose Kiel temperature probe. The pressure output was connected to the same upright manometer board as the pressure distribution ports. The thermocouple for temperature measurement was connected to a Leeds and Northrup portable potentiometer.

3. Visualization of Separation

Separation lines were visualized with soft twine tufts placed along the diverging planes. The lines of tufts spanned the test section to within three inches of each

sidewall and were spaced at one inch intervals across the test section and two inch intervals down the plane as seen in Fig. III.11.

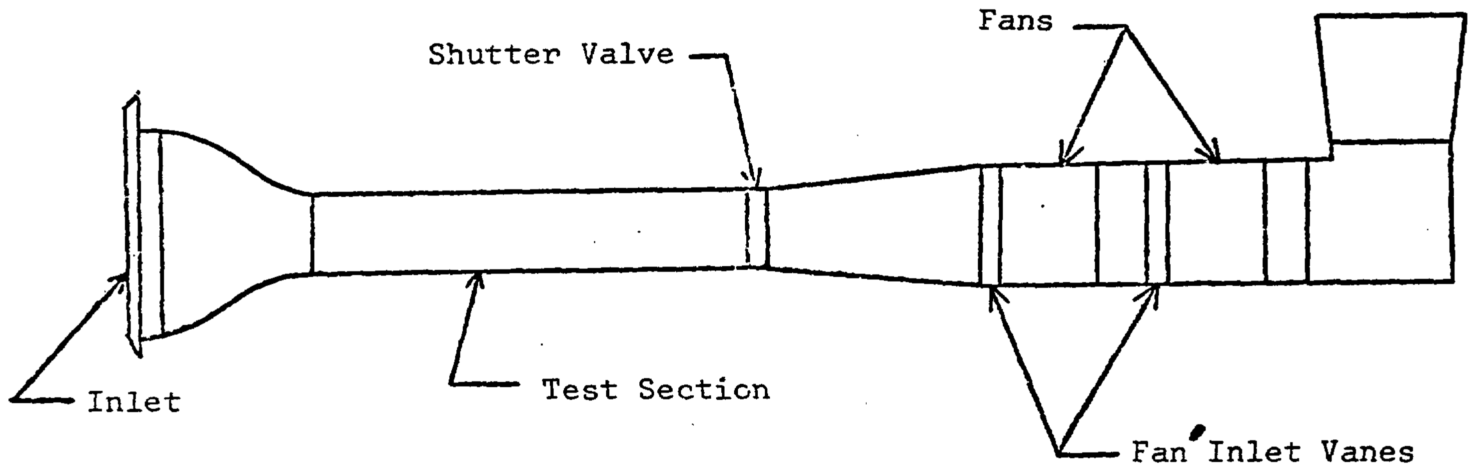

Figure III.1. Plan View of Wind Tunnel.

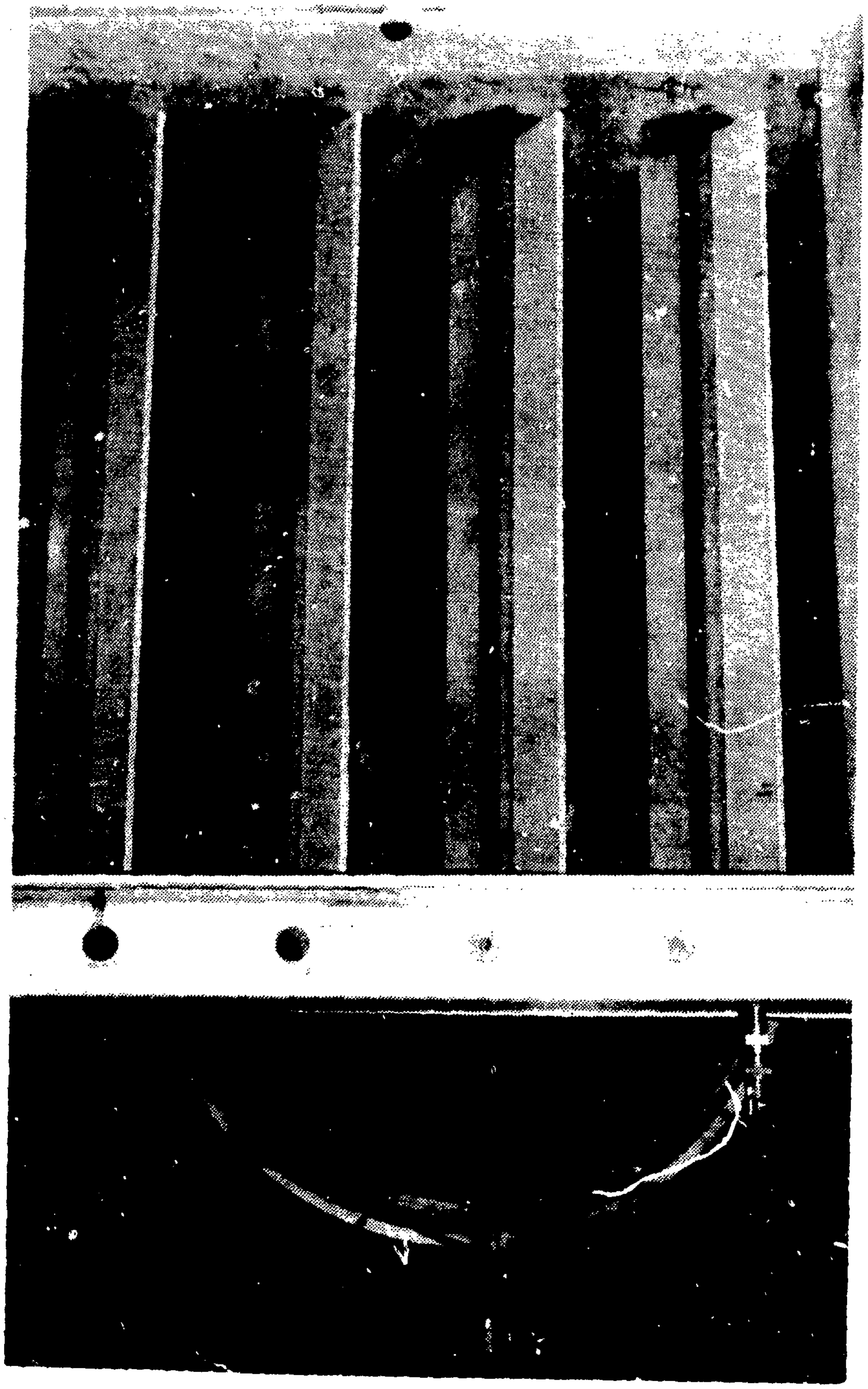

Figure III.2. Photograph of Rotating Shutter Valve.

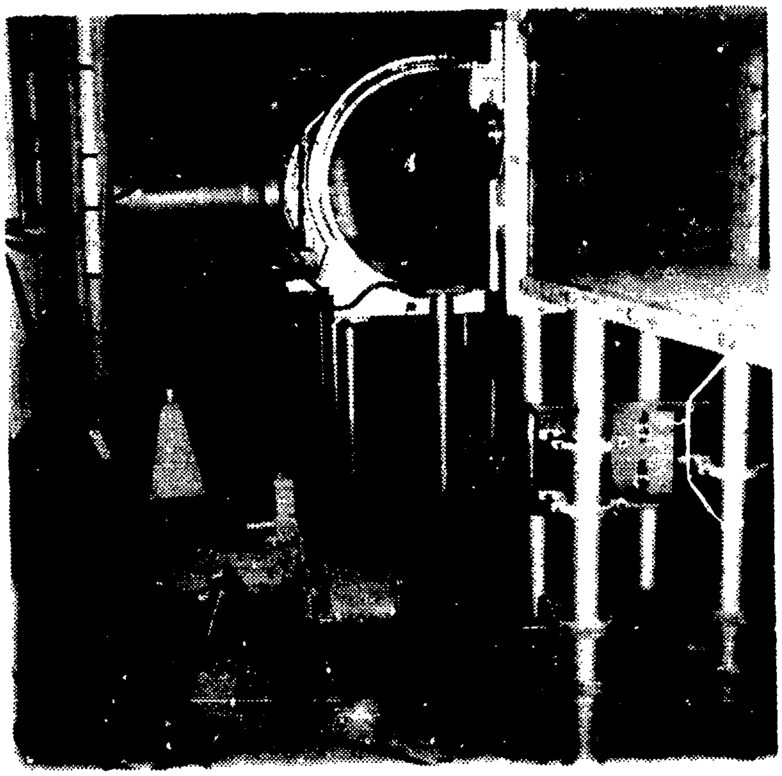

Figure III.3. Photograph of Shutter Valve Drive Mechanism.

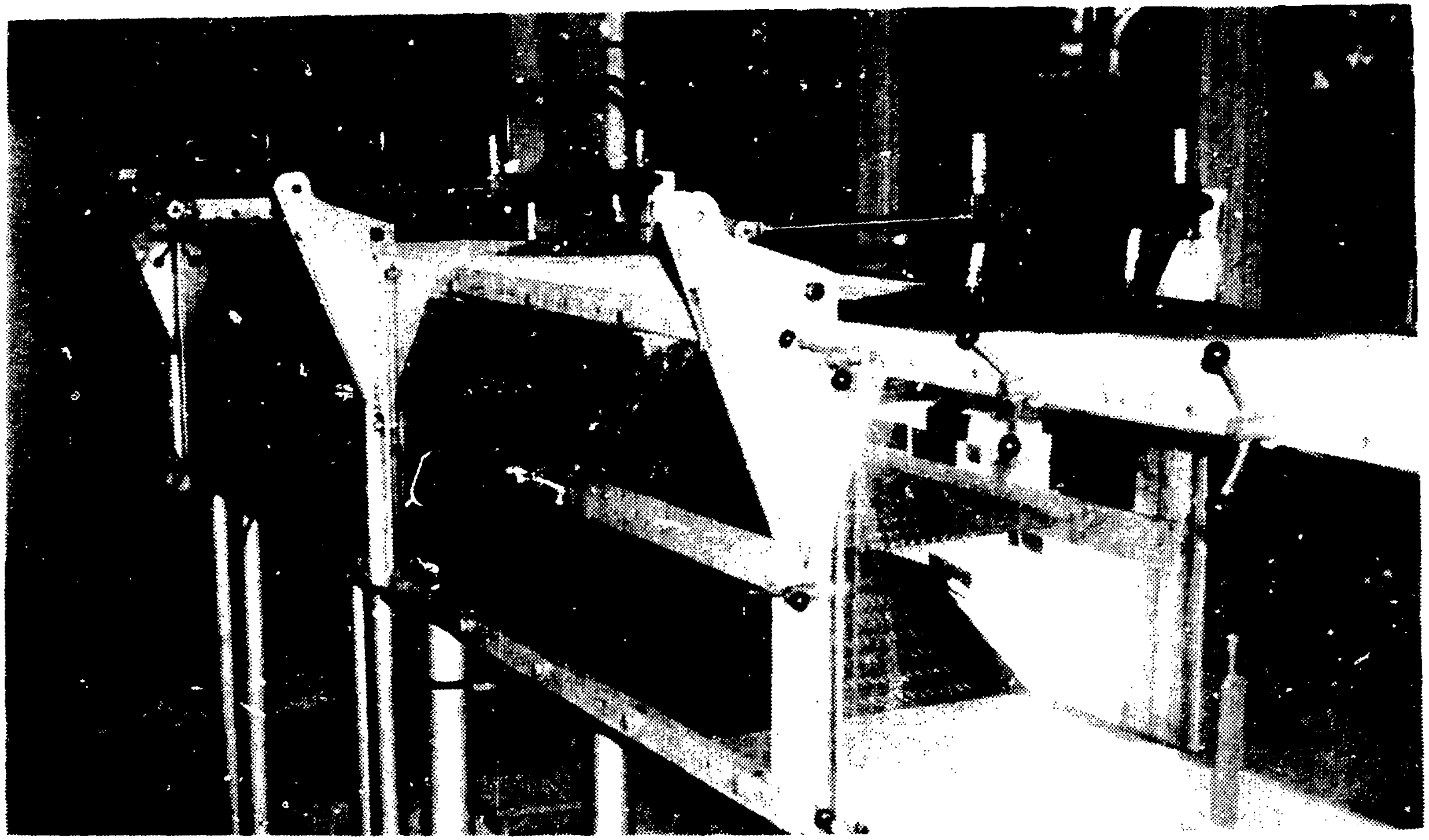

Figure III.4. Photograph of Wind Tunnel Test Section Closed.

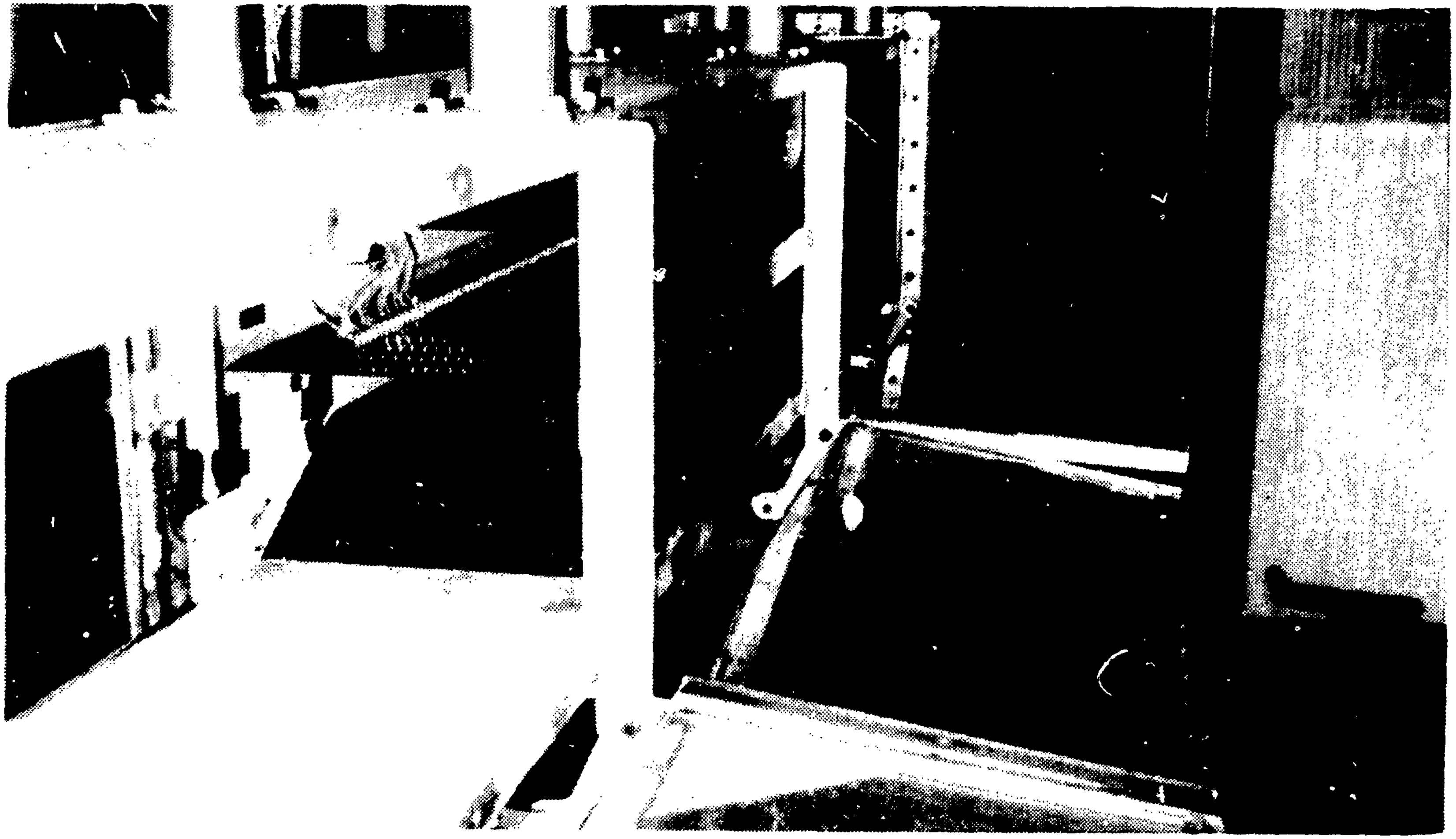

Figure III.5. Photograph of Test Section Open with Model.

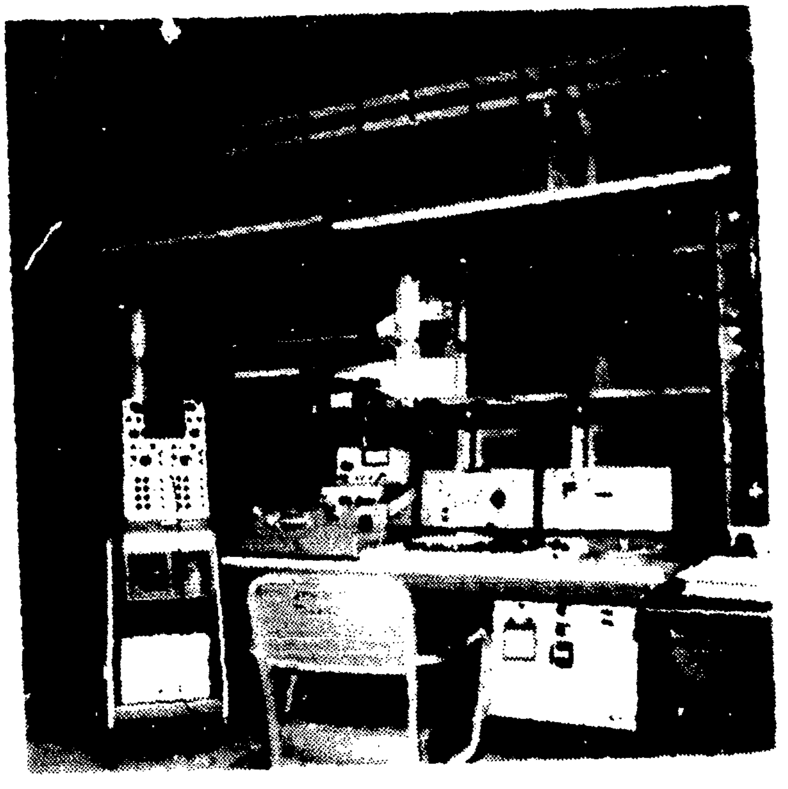

Figure III.6. Photograph of Test Section and Control Console.

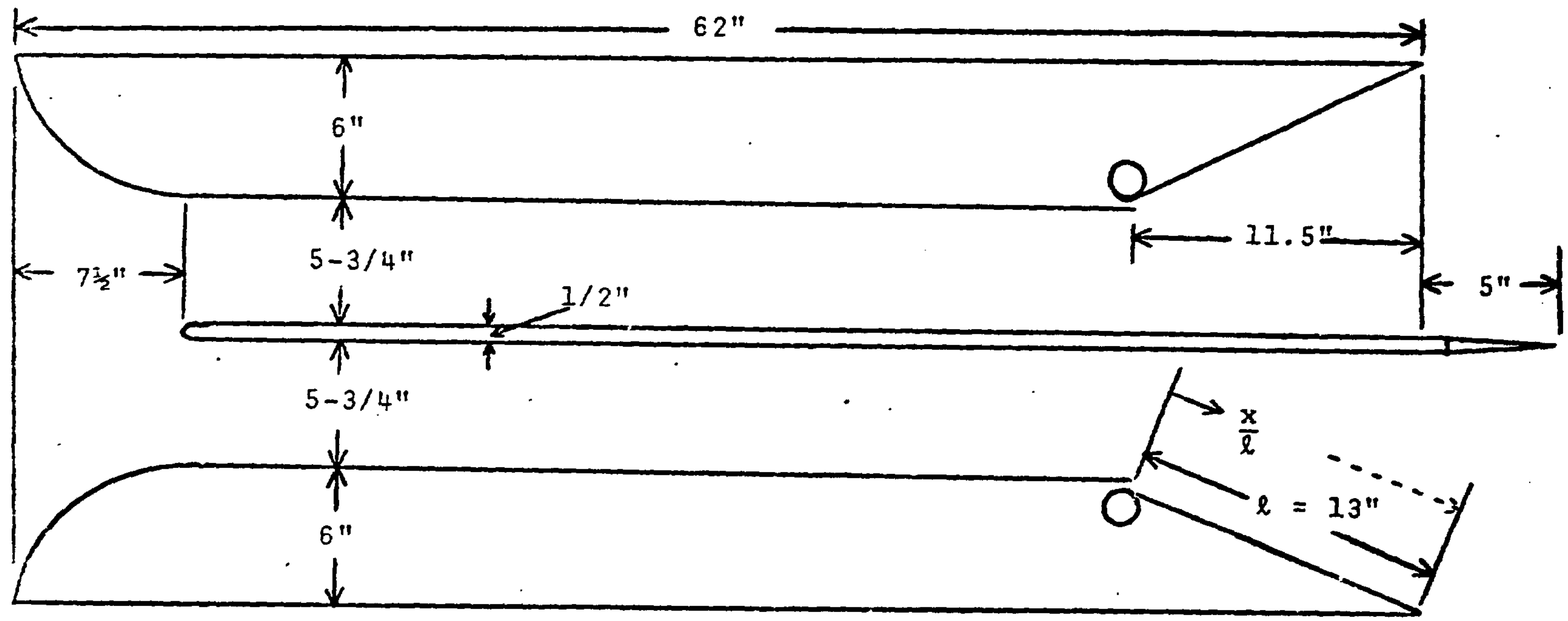

Figure III.7. Drawing of Model and Plate.

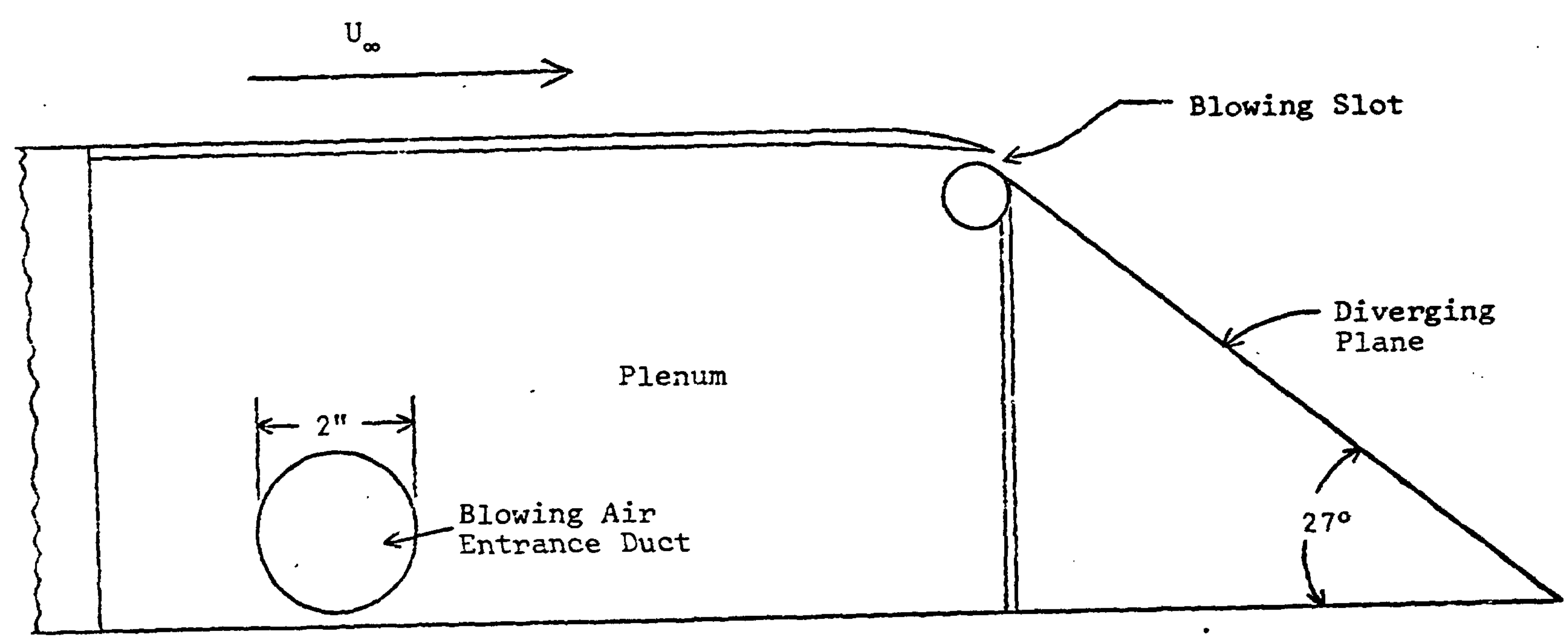

Figure III.8. Drawing of Plenum and Blowing Slot Configuration.

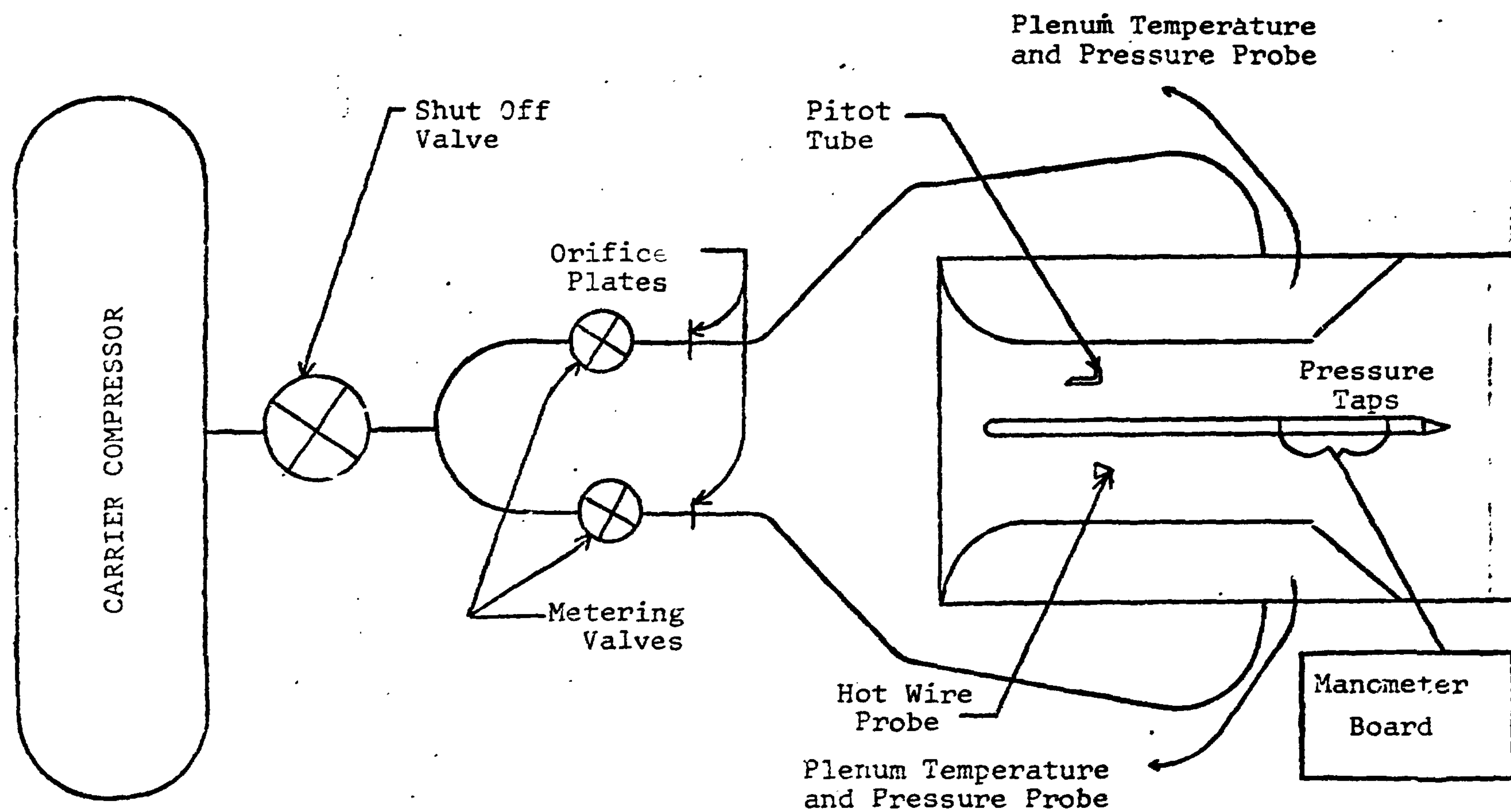

Figure III.9. Schematic of Test Setup.

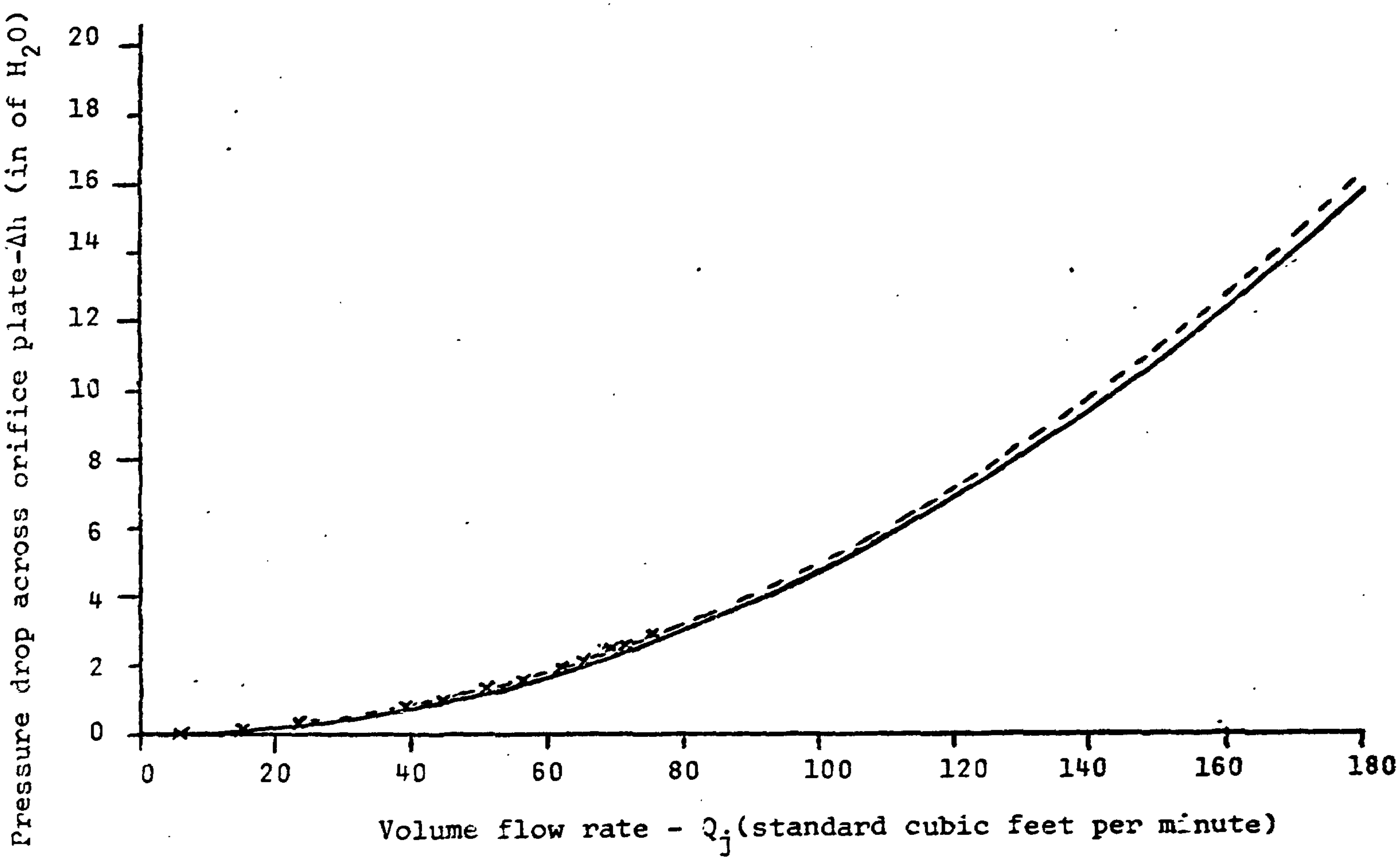

Figure III.10. Pressure Drop Across Orifice vs. Volume Flow of Air.

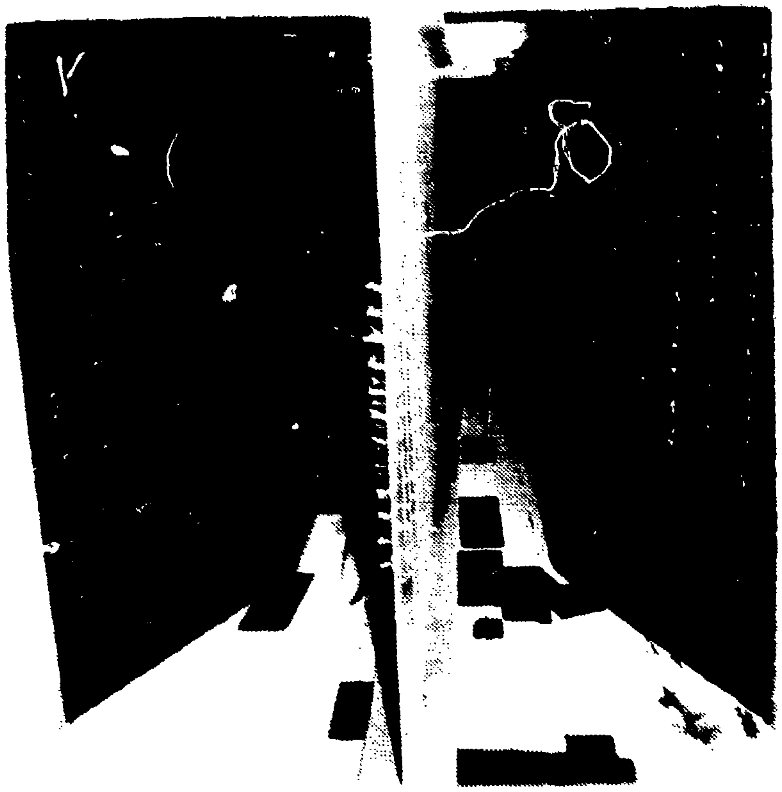

Figure III.11. Photograph of Diverging Planes from Downstream.

IV. TEST PROGRAM

A. EXPERIMENTAL PROCEDURE

The basic test program was to find, for some value of freestream dynamic pressure, the value of blowing coefficient that was just sufficient to maintain an attached boundary layer, then to study the effects of varying the frequency of oscillation on the blowing coefficient required.

The first problem was to select values of mean freestream dynamic pressure for the study. The dynamic pressures chosen were those which indicated 5, 7.5, and 10 centimeters on the micro-manometer. This decision was based on three criteria:

1. Below 5 centimeters the atmospheric wind conditions at the inlet began to affect the test section conditions.

2. Above 10 centimeters the fans could not maintain the pressure at higher oscillation frequencies. This could be remedied by opening the fan housing and altering the vane direction but this would have vastly increased the time required for runs and would have had an effect on test section conditions.

3. These three settings were easily read and maintained during tunnel operations.

These three dynamic pressures gave values of mean freestream velocity of about 96, 118, and 138 feet per second, respectively, although this varied slightly with oscillation frequency.

The initial tests were dictated by the wind tunnel set-up from previous work. The set of belts and pulleys connecting the electric drive motor to the shutter valve, at the beginning, corresponded to a frequency range of 2.48 to 14.4 cycles per second. Then on the basis of the previous test results the range was expanded outward to cover frequencies of 1.6 to 16 cycles per second. (See Results for detailed explanation.)

The detailed test procedure was as follows:

1. Start tunnel and stabilize at desired dynamic pressure.

2. Adjust blowing to barely maintain attached flow down the diverging plane.

3. Take data for pressure distribution, blower plenum conditions and mass flow of blown air.

4. Start shutter valve and set to the desired frequency. Adjust dynamic pressure as necessary.

5. Repeat step 2.

6. Take data for magnitude of oscillation.

7. Repeat step 3.

8. Adjust shutter valve for new frequency and repeat steps 5, 6, and 7 in order.

B. DATA REDUCTION

The data reduction was accomplished using a Fortran language computer program on the IBM 360/67 computer located at the Naval Postgraduate School. The program is shown in a separate section beginning on page 61.

The calculations involved are of mean freestream static pressure, density, velocity and magnitude of the oscillation of mean freestream velocity in percent. Then the pressure distribution was non-dimensionalized with respect to free-stream dynamic pressure. Finally the blowing coefficient was calculated for the upper and lower blowers.

In addition the computer program plotted the pressure distribution for constant frequency and blowing coefficient versus frequency for constant freestream dynamic pressure. The pressure distribution plots were used for further, manual, data reduction. The blowing coefficient variation with frequency was a guide to further experimentation in the early stages, and for presentation of results.

V. RESULTS

The results of this study are presented in Figures V.2 through V.11.

One of the greatest difficulties encountered during experimentation was establishing a reasonable definition of separation in an oscillating flow. Turbulent oscillating flow does not lend itself to a single, unambiguous definition of separation because the flow tends to separate progressively. Flow areas may be identified that are attached always, separated always, and alternately attached and separated during a single cycle of oscillation. The method of visualizing separation with rows of tufts led to the definition used in this study. It was assumed that separation had occurred if the flow reversed itself within the boundary layer during any part of a cycle. The definition used in this study does not coincide with Despard's definition [Ref. 12] for separation in laminar boundary layers. Despard proposed separation as commencing with the initial occurrence of zero velocity or reverse flow throughout the entire cycle. Despard's definition cannot be easily used for flow visualization studies. Preliminary testing revealed that below about 1.6 cycles per second the flow acted in a quasi-steady manner. That is, the blowing required to maintain attachment was dependent on the instantaneous velocity. Therefore it was necessary to provide blowing equal to that required by the maximum magnitude of the adverse

pressure gradient during a cycle. Also, above 16 cycles per second, the oscillations were so rapid that it became impossible to detect, by eye, the onset of separation with the method in use. In fact, as the frequency approached 16 cycles per second the decision as to whether to flow was or was not separated became more arbitrary because the tufts would oscillate at a frequency close to the limit of the eyes ability to discern change. For the reasons cited above the study was continued to the frequency range from 1.6 to 16 cycles per second.

One other problem encountered with the experimental setup was that of three dimensional flow in the test section. It has been suggested that the study of separation on a flat plate in a turbulent oscillating flow with strong adverse pressure gradient could be accomplished by using a model similar to that used in this study. To achieve this it would be necessary to have the flow attached across the entire plane of the diverging section. This should allow the boundary layer growing on the flat plate to become detached due to the impressed pressure gradient. Tufts were placed, therefore, on both the upper and lower surfaces of the flat plate, as well as along the diverging plane. Boundary layer growth in the corners and on the sidewalls caused a wedge shaped area of separation to appear on the diverging plane as shown in Figure V.1. Tufts close to the sidewalls indicated this corner-sidewall separation but those close to the centerline of the tunnel indicated the flow was still

attached to the diverging plane. It was necessary, therefore, to observe only tufts in the center of the test section during this study. The flow was considered attached if at least five contiguous tufts in one row indicated that the flow was attached. This definition was somewhat arbitrary, but its consistent application led to some meaningful trends. Some separation did occur from the bottom side of the plate when the mean freestream velocity was 138 feet per second with high blowing coefficient. Unfortunately, this separation was not reproducible. The flow never did detach from the top side of the plate. These observations show that it will be necessary to blow along the sidewalls to prevent the corner separation, thereby ensuring more predictable separation characteristics on the plate.

To analyze the results it was necessary to determine the parameters on which C_{μ_R} (the minimum blowing required to maintain attached flow) is dependent. It was assumed that the jet velocity required V_{j_R} to attach the flow was a function of the density, ρ; mean freestream flow velocity, U_∞; the length of the plane on which attachment is measured, ℓ; viscosity, μ; the magnitude of the perturbation of the freestream velocity, ΔU_∞; the frequency of the oscillation, ω; the slot height, h; and the effect of the pressure gradient as measured by $\Delta P_E \cdot \delta$, where δ is the boundary layer thickness at the diffuser exit and ΔP_E the pressure difference from the reference or undisturbed condition to the exit. This dependence is expressed as Equation V-1.

$$V_{j_R} = f_1[\rho, U_\infty, \ell, \Delta P_E \cdot \delta, \mu, \Delta U_\infty, \omega, h]. \quad \text{(V-1)}$$

Bernoulli's equation may be used to express the pressure coefficient as

$$\frac{\Delta P_E}{\frac{1}{2}\rho U_\infty^2} = \left[1 - \frac{U_E^2}{U_\infty^2} \right] \quad \text{(V-2)}$$

where U_E is the velocity at the exit of the diverging section. Substituting V-2 into V-1 and non-dimensionalizing with respect to ρ, U_∞, and ℓ leads to

$$\left(\frac{V_{j_R}}{U_\infty} \right) = f_2\left\{ \left(\frac{\delta}{\ell} \right) \cdot \left[1 - \frac{U_E^2}{U_\infty^2} \right], \left(\frac{\mu}{\rho U_\infty \ell} \right), \left(\frac{\omega \ell}{U_\infty} \right), \left(\frac{\Delta U_\infty}{U_\infty} \right), \left(\frac{h}{\ell} \right) \right\}. \quad \text{(V-3)}$$

It is convenient to replace $\mu/\rho U_\infty \ell$ by its reciprocal, the Reynolds number.

C_{μ_R} may then be expressed as

$$C_{\mu_R} = \frac{\dot{m}_j V_{j_R}}{\frac{1}{2}\rho U_\infty^2 S} = \frac{\rho b h V_{j_R}^2}{\frac{1}{2}\rho U_\infty^2 (b\ell)} \quad \text{(V-4)}$$

where b is the width of the slot. This may be simplified to

$$C_{\mu_R} = 2\left(\frac{h}{\ell} \right)\left(\frac{V_{j_R}}{U_\infty} \right)^2. \quad \text{(V-5)}$$

From equation V-3 and V-5 the critical blowing coefficient may be written as

$$C_{\mu_R} = f_3\left\{ \left(\frac{\delta}{\ell}\right) \cdot \left[1 - \frac{U_E^2}{U_\infty^2} \right], \left(\frac{\rho U_\infty \ell}{\mu} \right), \left(\frac{\ell \omega}{U_\infty}\right), \left(\frac{\Delta U_\infty}{U_\infty} \right), \left(\frac{h}{\ell} \right) \right\} \quad \text{(V-6)}$$

Equation V-6 shows that C_{μ_R} is a function of five independent parameters. In the experimental study the pressure gradient parameter

$$\left(\frac{\delta}{\ell} \right) \left[1 - \frac{U_E^2}{U_\infty^2} \right]$$

was determined by the model and tunnel configuration. Although the pressure gradient was measured (see later discussion) there was no measurement or control of δ possible in this study. This parameter may be most important and further studies should be made while observing δ. Three Reynolds numbers were considered; 5.93×10^5, 7.31×10^5 and 8.53×10^5. These Reynolds numbers corresponded to test section freestream velocities of 96 fps, 118 fps, and 138 feet per second (dynamic pressures of 5.0, 7.5, and 10.0 centimeters of water), respectively.

Oscillation frequency was varied continuously between 1.6 and 16 cycles per second which resulted in a reduced frequency range of approximately .1 to 1.1. The percent perturbation of velocity $\Delta U_\infty / U_\infty$ was a function of frequency, shutter valve plate size, and freestream dynamic pressure. It was not independently controllable in this study since a single plate size was used. $\Delta U_\infty / U_\infty$, therefore was dependent on frequency and dynamic pressure. Since $\Delta U_\infty / U_\infty$ did vary as the reduced frequency was changed, the resulting frequency variation in C_{μ_R} measured could not be determined at constant values of all the correlation parameters.

Reference [18] states that experiments have shown that for steady flows C_{μ_R} is not a function of h/ℓ for high slot Reynolds Numbers, $V_j h/\nu$. Therefore, h/ℓ is normally omitted from Equation V-6. Blowing characteristics could vary significantly with slot height at low values of the slot Reynolds

numbers. Slot Reynolds numbers encountered in this study varied from 6.06×10^3 to 11.56×10^3 for the upper slot, and 6.42×10^3 to 11.74×10^3 for the lower slot. To independently check the results of Ref. [18] for the case of unsteady flows, this study used two non-dimensional slot heights of 3.15×10^{-3} and 4.23×10^{-3}.

Figures V-2, 3 and 4 clearly indicate that frequency has a definite effect on blowing requirements to maintain an attached flow. At a Reynolds number of 5.93×10^5, Figure V-2 shows that there is no apparent change in C_{μ_R} from the non-oscillating condition to a reduced frequency of 0.5 where C_{μ_R} increases by approximately 30 percent. The required flowing gradually decreases through the remainder of the frequencies tested in this study. For the Reynolds number of 7.31×10^5, Figure V-3, the initial values of C_{μ_R} at a reduced frequency of 0.1 are approximately 40 percent above the non-oscillating condition. At a reduced frequency of 0.13, C_{μ_R} drops to approximately 30 percent greater. At 0.48 the blowing required increases to as much as 50 percent above the non-oscillating condition after which it drops back down to approximately 30 percent for the higher frequency oscillations. Figure V-4 shows the C_{μ_R} behavior for a Reynolds number of 8.53×10^5. It shows that a reduced frequency of C.08, C_{μ_R} is approximately 40 percent greater than the non-oscillating case. C_{μ_R} rises rapidly to 100 percent higher at a reduced frequency of 0.12. C_{μ_R} stays at this level until a reduced frequency of 0.29 is reached where it drops to 50 percent above the non-oscillating

condition. At a reduced frequency of 0.4, the blowing required then rises rapidly to 70 percent above the non-oscillating condition followed by a gradual decrease through the remainder of the frequencies studied.

There was a significant difference between C_{μ_R} for the upper and lower blowers. This was not expected, in spite of the differences in slot heights, as indicated in previous discussion, because C_μ is a momentum coefficient. Therefore, although the upper blower had less mass flow, its greater jet velocity should produce the same attachment effectiveness as the lower blower. The upper blower C_{μ_R} was approximately 15 percent higher than that of the lower blower at R_ℓ of 5.93×10^5. For R_ℓ of 8.53×10^5 the difference was 20 percent. But at R_ℓ equal to 7.31×10^5, the upper blower required approximately 4 percent less blowing than the lower blower. This inconsistency, with test section velocity, of the difference between upper and lower C_{μ_R} might indicate that the upper and lower diverging sections experience different flow environments. Since separation is intimately linked with both previous boundary layer growth and disturbing influences, the C_{μ_R} differences may be explained by the presence of some downstream flow asymmetry that is a function of test section velocity.

It was recognized that the variation in C_{μ_R} was dependent on the pressure gradient and the magnitude of the perturbation of free stream velocity, both of which exhibit variations with frequency in this test setup. The median

pressure coefficient, C_p, on the flat plate was plotted versus position, x, along the plate. x/ℓ equal to zero corresponds to the blowing slot location. Typical pressure distributions are shown in Figure V-5 for the cases of steady flow with no blowing, steady flow with blowing, and oscillating flow with blowing respectively. The pressure gradient was determined by estimating the slope of the best straight line fit of the plotted pressures. The resulting slope was plotted against the reduced frequency for each of the freestream velocities run. These data showed similar variation of C_{p_x} versus reduced frequency and so are plotted together in Figure V-6. An examination of Figure V-6 shows that the pressure gradient variation with frequency was not the primary cause of the exhibited large variations of C_{μ_R} with frequency. Similar plots of percent perturbation in freestream velocity, as measured by the hot wire, versus reduced frequency are shown in Figures V-7, 8 and 9. The cases of R_ℓ equal to 5.93×10^5 and 7.31×10^5 show a gradual, almost linear, decrease of perturbation velocity with frequency but the R_ℓ of 8.53×10^5 case showed the characteristics seen in Figure V-9. There was, however, no indication that these variations in the velocity perturbation were responsible for the shape of the large variation of C_{μ_R} with frequency seen in Figure V-2, 3 and 4.

The blowing requirement to maintain attached flow has been shown to be frequency dependent. This dependence exhibits characteristics which suggest resonant behavior.

This resonance might be the result of flow confinement. Wave reflections, due to the tunnel walls, could affect the conditions in the test section. These reflected waves could either reinforce or dissipate the shutter valve induced pressure pulses. Another source of resonance lies in the physical makeup of the tunnel. It was observed during the experimental runs that certain frequency bands at each tunnel test section velocity made the wind tunnel vibrate a great deal, sometimes causing the test section to be traveling as much as two inches longitudinally. These resonant frequency bands are shown in Figures V-2, 3 and 4. This resonant behavior of the tunnel occurred around a frequency of approximately 8.7 cps. Tunnel vibrational modes are seen to be influencing the blowing characteristics observed. Different test configurations may exhibit different characteristics.

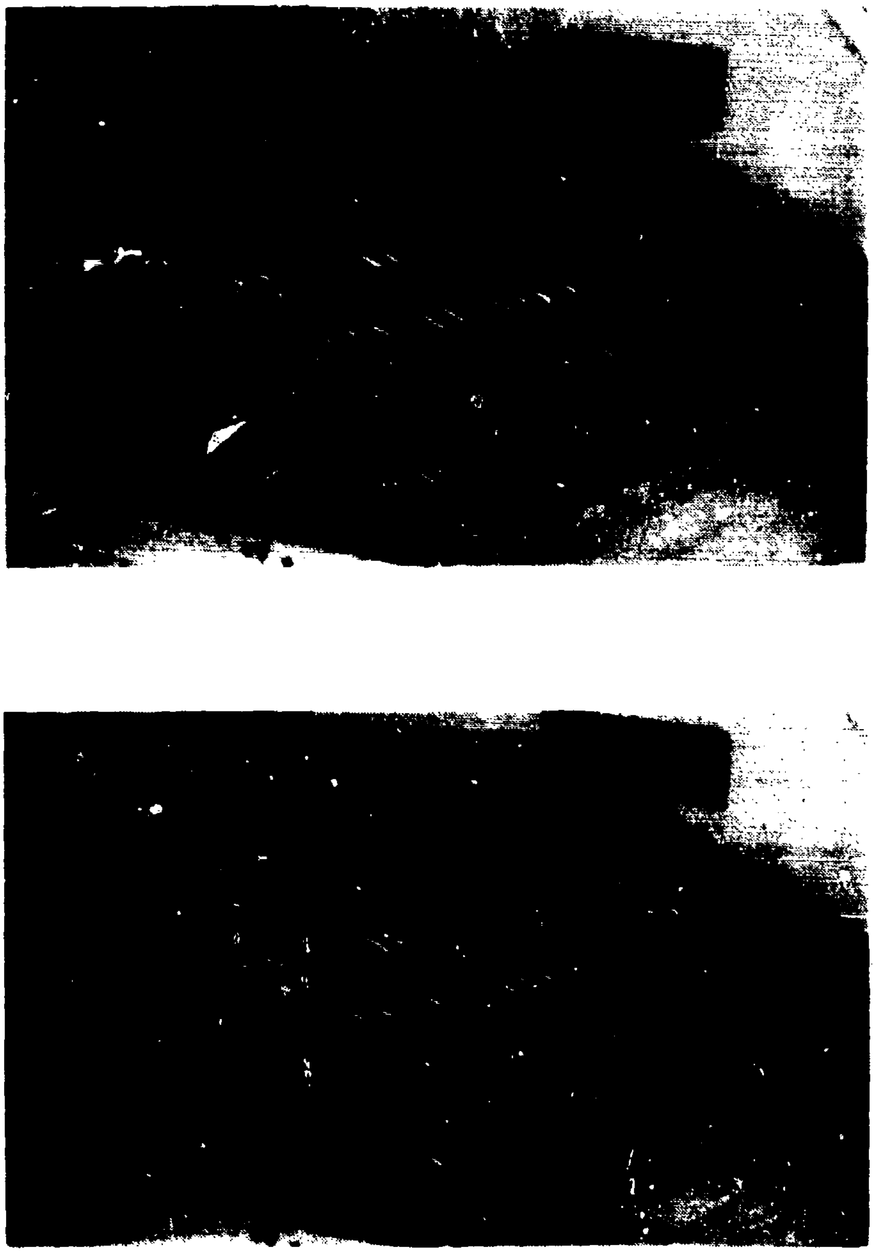

Figure V.1. Photograph of Tuft Showing Corner Sidewall Separation.

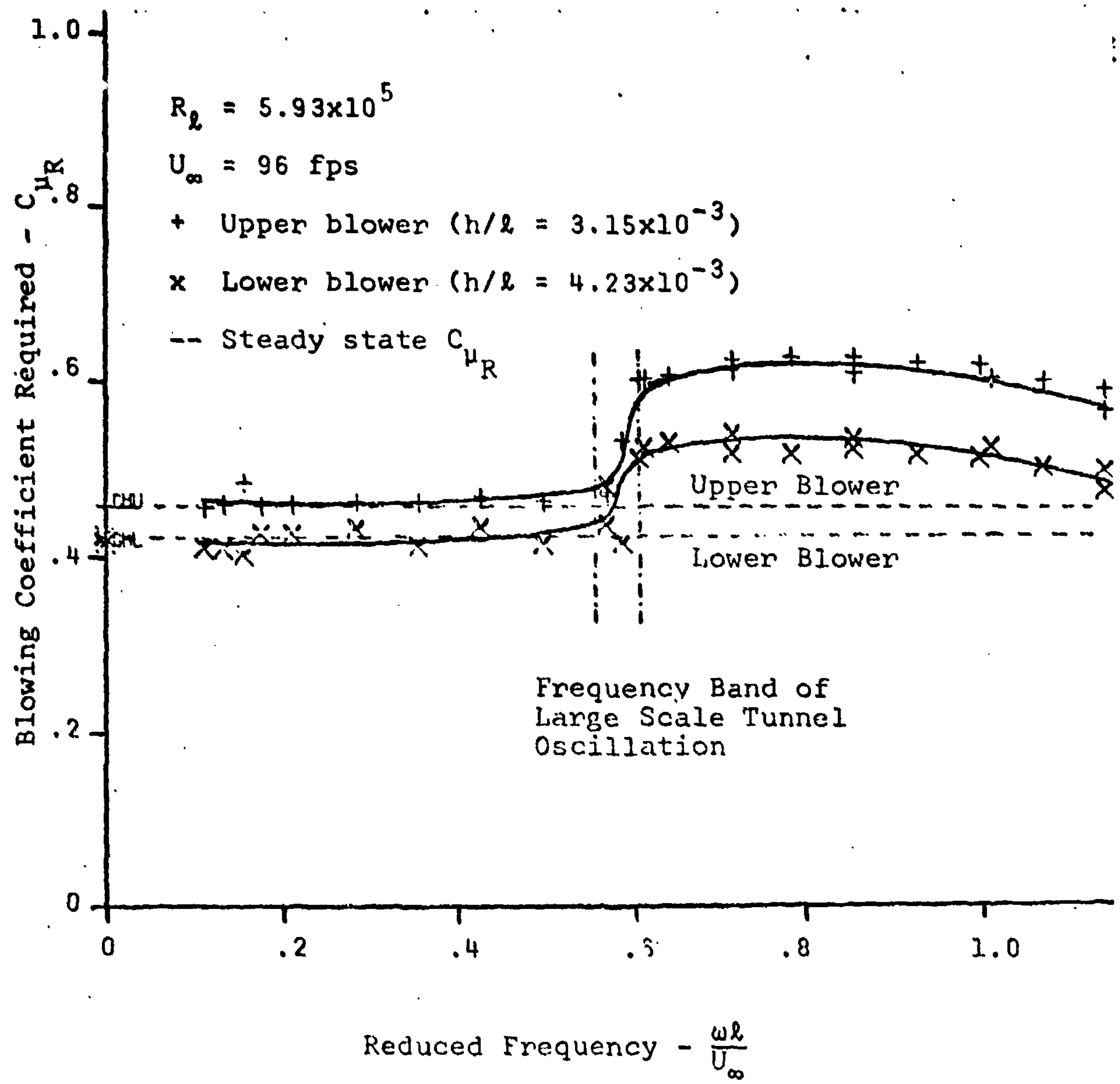

Figure V.2. Blowing Coefficient Required vs. Frequency, $R_\ell = 5.93 \times 10^5$.

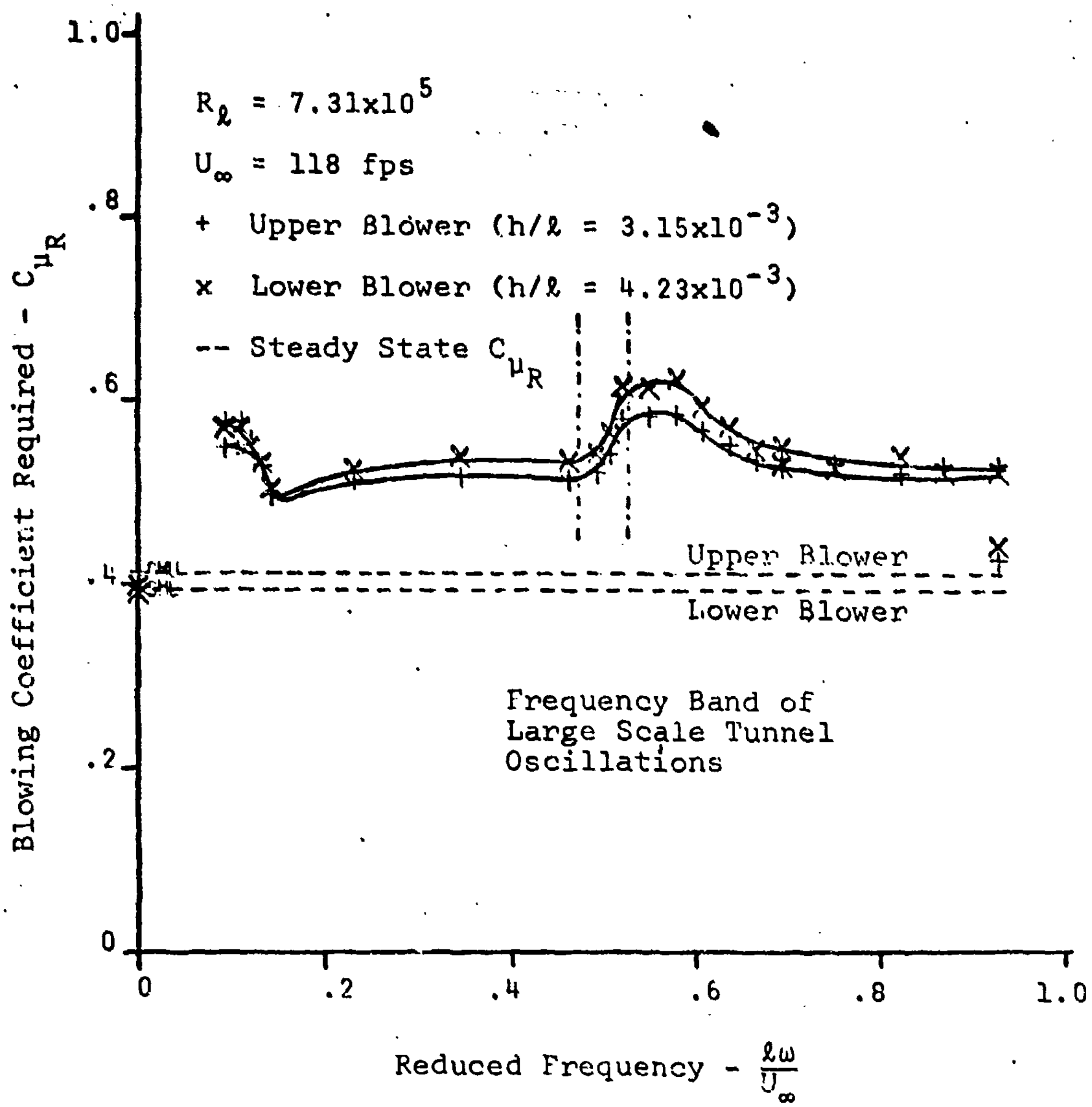

Figure V.3. Blowing Coefficient Required vs. Frequency, R_ℓ = 7.31x10^5.

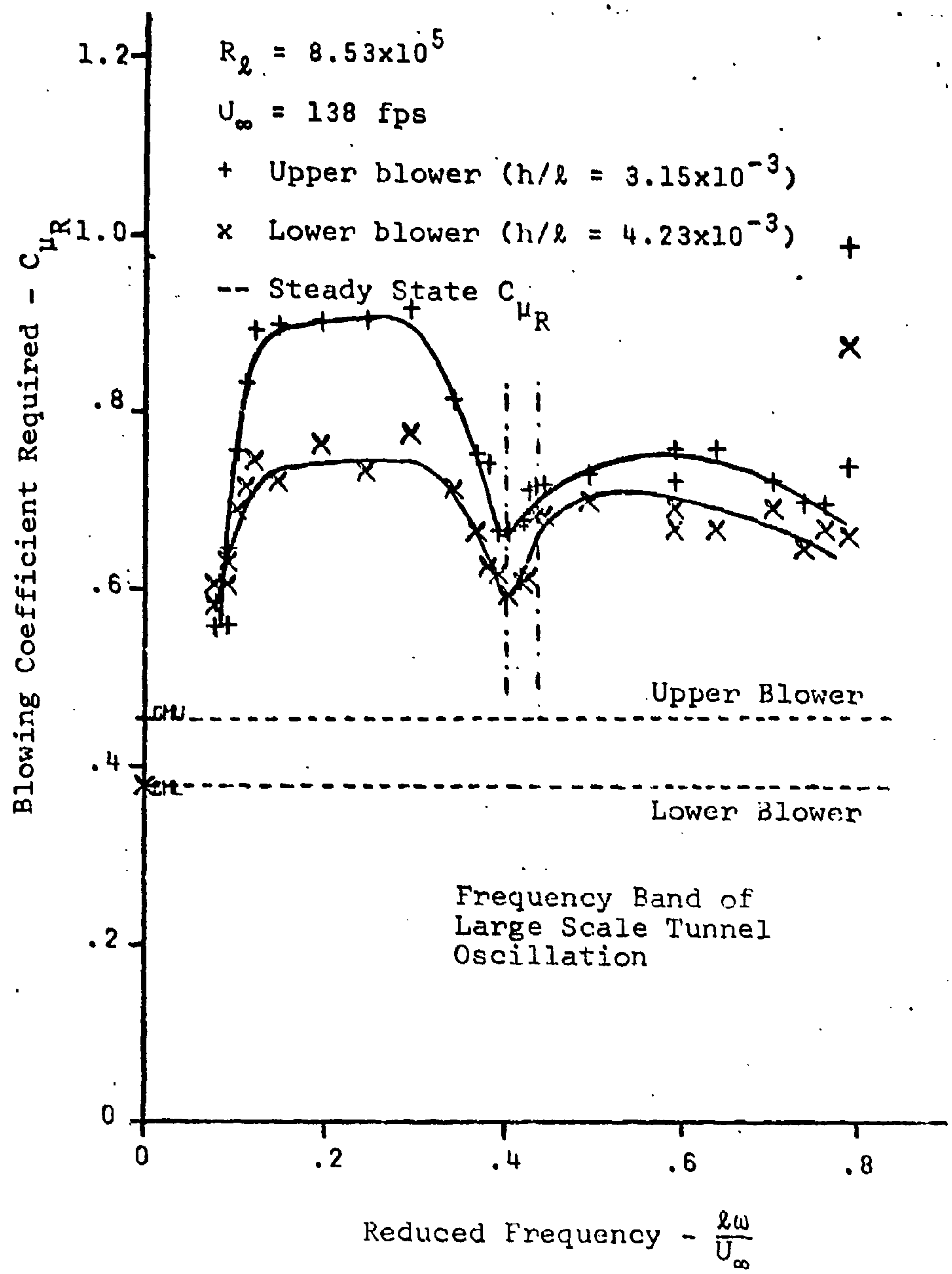

Figure V.4. Blowing Coefficient Required vs. Frequency, $R_\ell = 8.53\times10^5$.

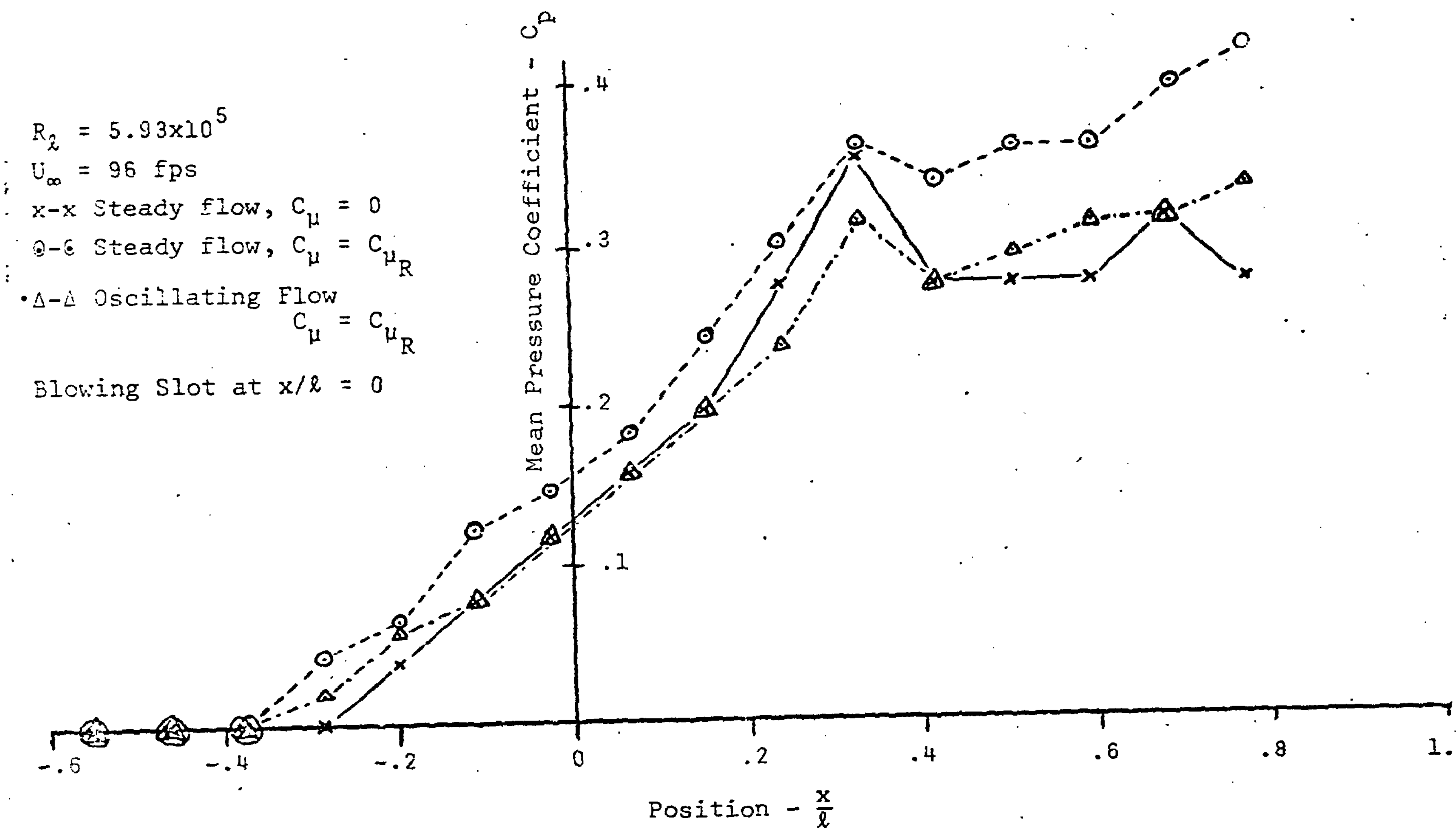

Figure V.5. Pressure Coefficient vs. Position.

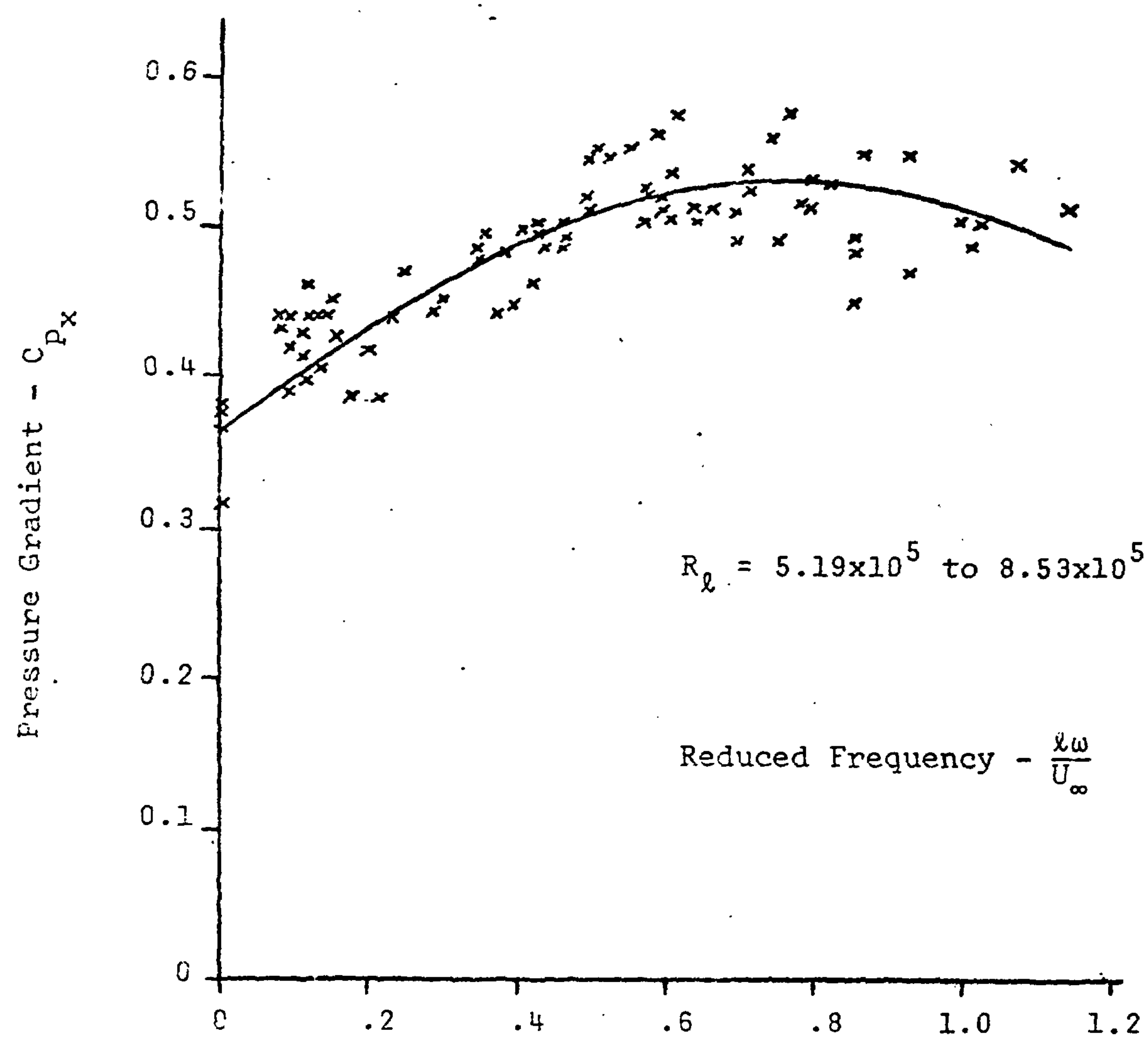

Figure V.6. Pressure Gradient vs. Frequency

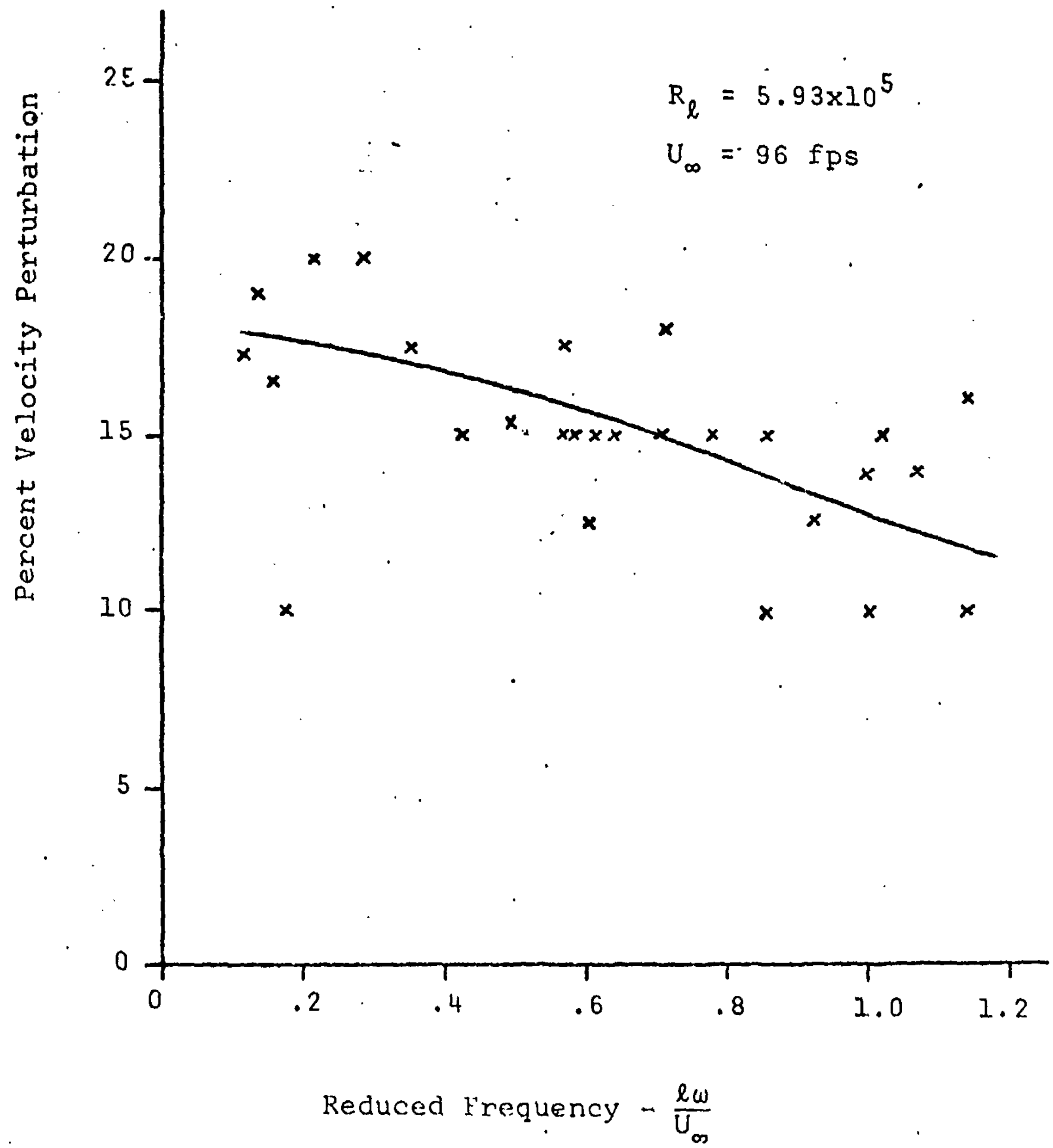

Figure V.7. Velocity Perturbation vs. Frequency, $R_\ell = 5.93\times10^5$.

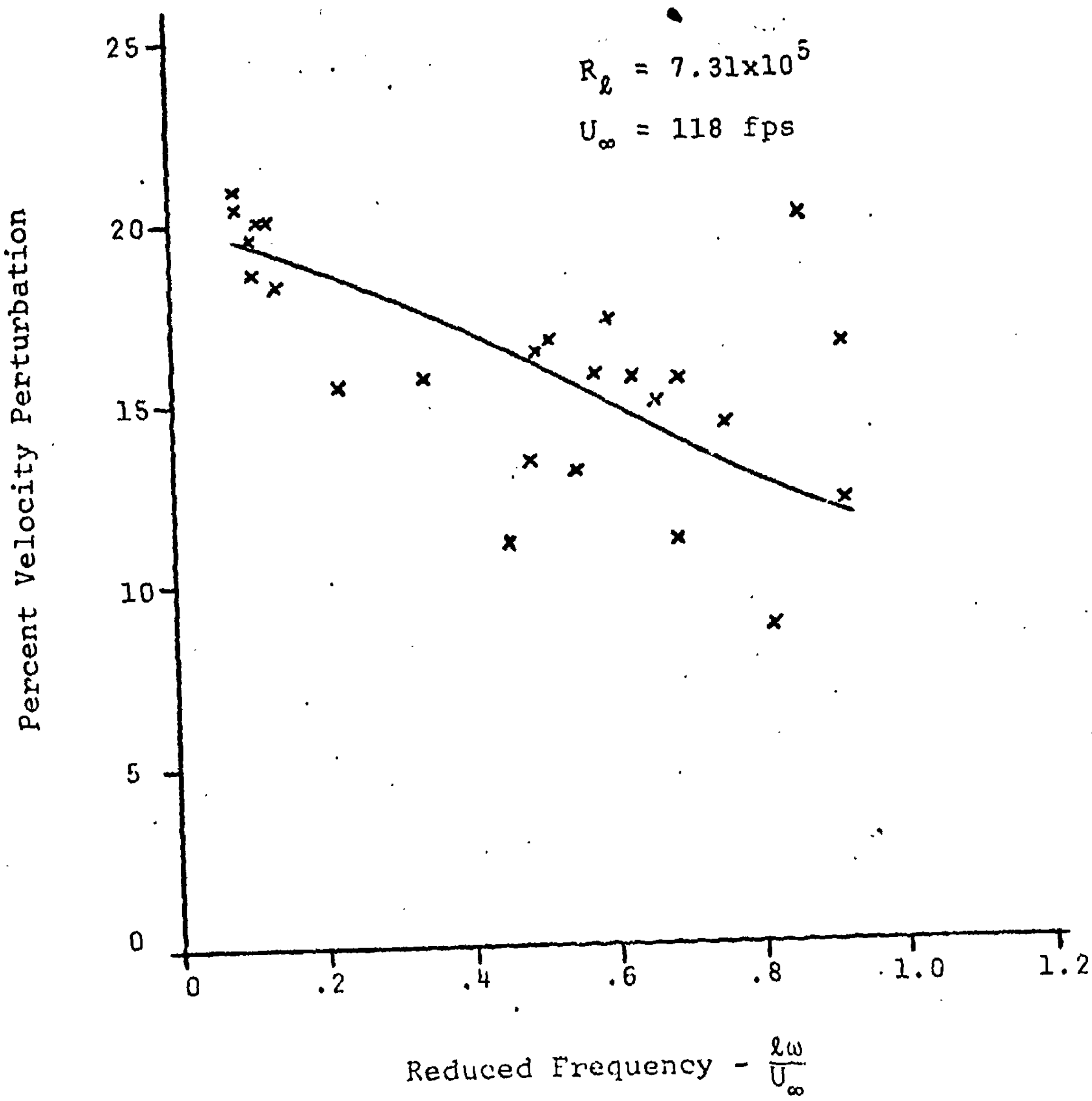

Figure V.8. Velocity Perturbation vs. Frequency, $R_\ell = 7.31 \times 10^5$.

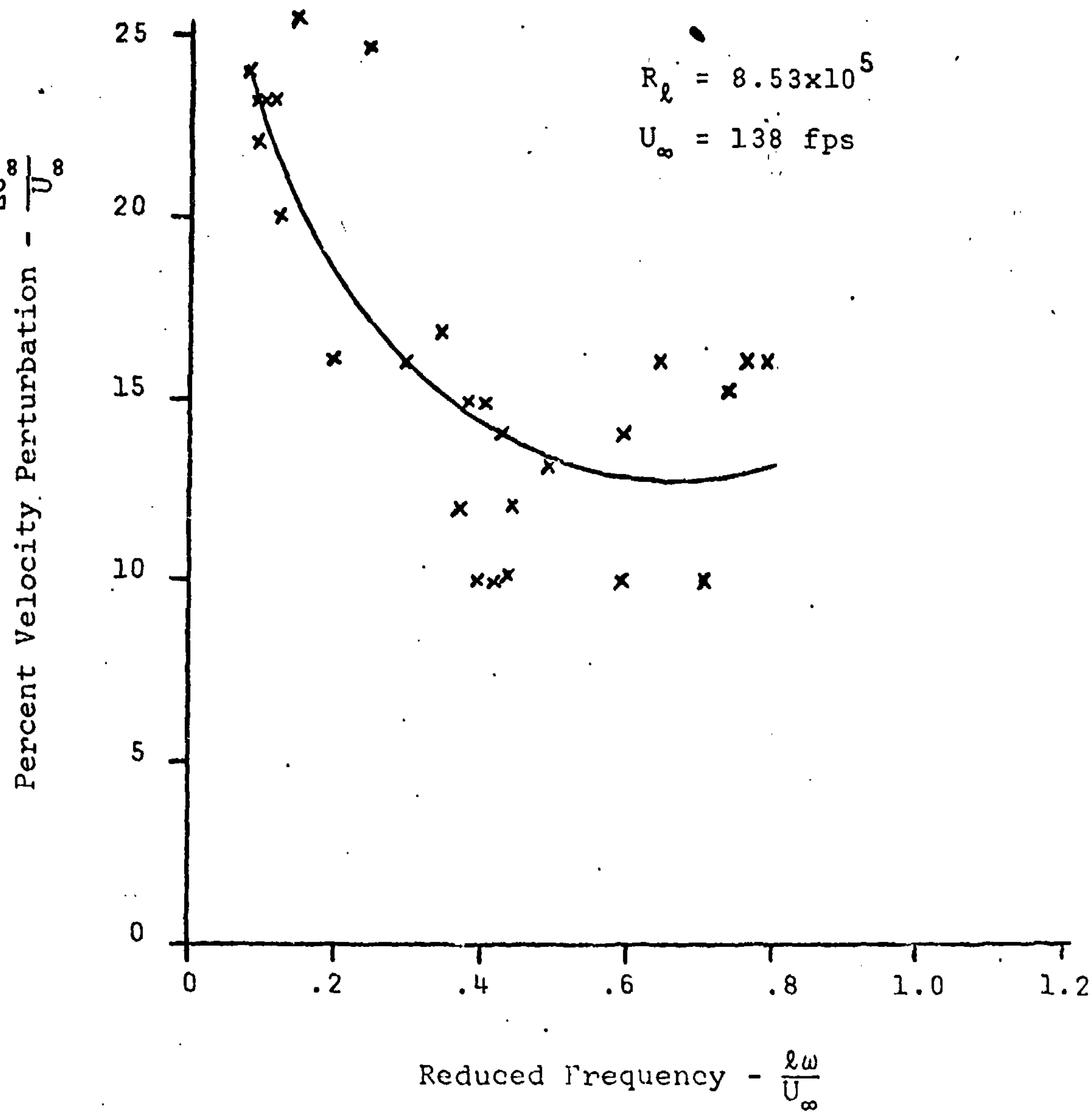

Figure V.9. Velocity Perturbation vs. Frequency, $R_\ell = 8.53\times10^5$.

VI. CONCLUSIONS

From the results obtained, the following conclusions may be drawn:

1. There is a definite effect on the blowing required to maintain an attached boundary layer in a strong adverse pressure gradient as oscillations are superimposed on the freestream velocity and the frequency is varied.

2. The frequency dependence of the blowing requirements exhibits characteristics which suggest resonant behavior.

3. Considerable three-dimensional flow is produced in the present test setup and sidewall blowing will be required to produce two-dimensional separation on the plate.

VII. RECOMMENDATIONS

1. C_{μ_R} is a function of the five parameters discussed in the Results section. More tests should be made in which only one of these is varied at a time. As discussed earlier, measurement of the boundary layer thickness is most desirable.

2. The velocity profiles throughout the flow field need to be studied as a function of time while varying oscillation frequency. To accomplish this a method for flow measurement must be developed which will fulfill the following requirements; non-interference with the flow, capable of measuring turbulent variations, capable of scanning a relatively large section of the flow, and capable of resolving rapid changes in flow velocities at high oscillation frequencies.

3. An investigation of the natural frequencies of the tunnel-model-air flow configuration should be made to determine the effects on pressure gradient, magnitude of oscillating velocity perturbation, and blowing requirements to maintain an attached boundary layer.

4. Sidewall blowing should be used to ensure two dimensional separation of the flat plate for further studies.

COMPUTER PROGRAM

```
C     ******************************************************************
C     *                                                                *
C     *                                                                *
C     *  THIS PROGRAM CALCULATES THE FOLLOWING .                       *
C     *     1.  MEAN FREESTREAM VELOCITY IN FEET PER SECOND            *
C     *     2.  OSCILLATION IN RADIANS PER SECOND                      *
C     *     3.  FREESTREAM VELOCITY PERTURBITION IN PERCENT            *
C     *     4.  DIMENSIONLESS PRESSURE DISTRIBUTION                    *
C     *         A.  ALSO PLOTTED ON CALCOMP PLOTTER WITH THE           *
C     *             ABSCISSA THE X POSITION IN INCHES                  *
C     *             BEGINNING AT THE UPSTREAM POSITION AND             *
C     *             THE ORDINATE IS THE PRESSURE COEFFICIENT           *
C     *     5.  JET VELOCITY OF EJECTED AIR FOR BOTH UPPER             *
C     *         AND LOWER BLOWERS IN FEET PER SECOND                   *
C     *     6.  MASS FLOW OF EJECTED AIR IN                            *
C     *         POUNDS MASS/SECOND                                     *
C     *     7.  BLOWING COEFFICIENT FOR UPPER AND                      *
C     *         LOWER BLOWERS                                          *
C     *         A.  PLOTTED ON CALCOMP PLOTTER WITH THE                *
C     *             ABSCISSA THE FREQUENCY IN RADIANS AND              *
C     *             THE ORDINATE THE BLOWING COEFFICIENT               *
C     *  OUTPUT IS LINE PRINTED, SEPARATED BY FREQUENCY                *
C     *  AND IS LABELLED                                               *
C     *                                                                *
C     *                                                                *
C     ******************************************************************
C
C
C
C
C      INPUT REQUIRED
C         PATM = ATMOSPHERIC PRESSURE (INCHES OF MERCURY)
C         T = OUTSIDE AIR TEMPERATURE (DEGREES FAREHEIT)
C         FREQ = FREQUENCY (CYCLES PER SECOND)
C         Q = MEAN FREESTREAM DYNAMIC PRESSURE (CENTIMETERS
C            OF WATER)
C         QMAX = MAXIMUM MAGNITUDE OF VELOCITY OSCILATIONS
C            (VOLTS OUTPUT OF HOTWIRE ANEMOMETER)
C         QMIN = MINIMUM MAGNITUDE OF VELOCITY OSCILATIONS
C            (AS ABOVE)
C         PAMB = AMBIENT PRESSURE (CENTIMETERS OF WATER,
C            REFERENCE HEIGHT FROM MULTI-TUBE MANOMETER BOARD
C         P = PRESSURE DISTRIBUTION, 16 VALUES PUT IN 1X16
C            VECTOR (CENTIMETERS OF WATER)
C         P2U = PRESSURE JUST DOWNSTREAM OF THE ORIFICE PLATE
C            IN THE SUPPLY LINE TO THE UPPER BLOWER
C            (CENTIMETERS OF WATER)
C         P2L = PRESSURE AS ABOVE BUT LOWER BLOWER
C         VFLOU = VOLUME FLOW OF BLOWING AIR TO UPPER BLOWER
C            (CUBIC FEET PER MINUTE)
C         VFLOL = VOLUME FLOW AS ABOVE FOR LOWER BLOWER
C         TPU = PLENUM AIR TEMPERATURE, UPPER BLOWER PLENUM
C            (DEGREES FARENHEIT)
C         TPL = PLENUM AIR TEMPERATURE, LOWER BLOWER
C         PPU = PLENUM AIR PRESSURE, UPPER BLOWER
C            (CENTIMERS OF WATER DIFFERENCE FROM ATMOSPHERIC)
C         PPL = PLENUM AIR PRESSURE, LOWER BLOWER
C
C      INPUT GOES ON FOUR DATA CARDS, THE FIRST HAS 7 NUMBERS
C      THEY ARE, PATM, T, FREQ, Q, QMAX, QMIN, PAMB.
C      THE NEXT TWO CARD HAVE THE 16 NUMBERS OF PRESSURE
C      DISTRIBUTION.  THE LAST CARD HAS, P2U, VFLOU, TPU,
C      PPU, P2L, VFLOL, TPL, PPL.  THE NUMBERS ARE INPUT
C      AS F10.4
```

```
C
C
C     LINE OUTPUT
C         FREQUENCY (CYCLES PER SECOND)
C         Q (CENTIMETERS OF WATER)
C         VELOCITY (MEAN FREESTREAM IN FEET PER SECOND)
C         PERCENT (PERTURBATION OF VELOCITY)
C         OMEGA (OSCILATIONS IN RADIANS PER SECOND)
C         CMU (BLOWING COEFFICIENT, UPPER BLOWER)
C         VJU (JET VELOCITY, UPPER BLOWER IN FEET/SECOND
C         FLOU (MASS FLOW OF JET, UPPER BLOWER IN
C               POUNDS PER SECOND)
C         CML (BLOWING COEFFICIENT, LOWER)
C         VJL (JET VELOCITY, LOWER)
C         FLOL (JET MASS FLOW, LOWER)
C         STATIONS (PRESSURE DISTRIBUTION TAP POSITIONS
C                   WITH 1 AS THE DOWNSTREAM  POSITION)
C         CP (PRESSURE COEFFICENT AT STATION)
C
C
C     PLOTTED OUTPUT
C         PRESSURE COEFFICIENT VS X POSITION (WITH 1 BEING
C            UPSTREAM)
C         BLOWING COEFFICIENT VS OMEGA (PLOT OF CMU AND CML
C            VERSUS OMEGA FOR EACH INPUT DECK)
C
C
C
      DIMENSION CP(16,40),CMU(40),OMEGA(40),F(40),
     1PCSL(16),P(16),CML(40),LPOS(16),CP1(16),QA(40)
   10 FORMAT (7F10.4)
   15 FORMAT (8F10.4)
   20 FORMAT ('0',T8,'Q',T17,'VELOCITY',T30,'PERCENT',T44,
     1'OMEGA',T58,'CMU',T72,'VJU',T84,'FLOU',T98,'CML'
     1,T110,'VJL',T123,'FLOL')
   25 FORMAT ('0',10F13.5)
   30 FORMAT ('0',T19,'STATION',T37,'CP'/)
   35 FORMAT (' ',I20,F26.8)
   40 FORMAT ('1')
   45 FORMAT (6A8)
   50 FORMAT ('OLAST = ',I10)
   55 FORMAT ('OTHE FREQUENCY IS ',F10.5)
      REAL*8 LABEL1/'CML     '/
      REAL*8 LABEL2/'CMU     '/
      REAL*8 LABEL3/'        '/
      REAL*8 TITLE1(12)
      READ (5,45) TITLE1
      REAL*8 TITLE2(12)
      READ (5,45) TITLE2
      DO 1000 J=1,28
      READ (5,10) PATM,T,FREQ,Q,QMAX,QMIN,PAMB
      READ (5,15) P
      DO 100 K=1,16
      LPOS(K)=K
      PCSL(K)=LPOS(K)
  100 CONTINUE
      READ (5,15) P2U,VFLOU,TPU,PPU,P2L,VFLOL,TPL,PPL
C
C     CONVERT TEMPERATURES TO RANKINE
C
      TEMP=T+459.688
      TPL=TPL+459.688
      TPU=TPU+459.688
      QA(J)=Q
      F(J)=FREQ
C
C     CALCULATE OMEGA, MEAN FREESTREAM VELOCITY, AND
C     PERCENT PERTURBATION
C
      OMEGA(J)=FREQ*6.283185308
      PINF=(P(14)+P(15)+P(16))/3.0
      RHO=((2.0*PAMB)-PINF)*PATM*.041206962D0/PAMB/TEMP
```

```
      VEL=2.020916944D0*SCRT(Q/RHO)
      PERCEN=((QMAX-QMIN)/(QMAX+QMIN))*100
C
C     NON DIMENSIONALIZE PRESSURE
C
      DO 200 I=1,16
      CP(I,J)=(PINF-P(I))/Q
  200 CONTINUE
C
C     CALCULATE BLOWING PARAMETERS
C
      RHO2U=(P2U+PATM)*.0412069621D0/TPU
      FLOU=VFLOU*RHO2U/60.0
      VJU=DSQRT(5454.50724D0*TPU*(1.0-(((2.0*PAMB)-PINF)
     1/((2.0*PAMB)-PPU))**.2862241256D0))
      CMU(J)=(FLOU*VJU)/(Q*4.332271417D0)
      RHO2L=(P2L+PATM)*.0412069621D0/TPL
      FLOL=VFLOL*RHO2L/60.0
      VJL=DSQRT(5454.50724D0*TPL*(1.0-(((2.0*PAMB)-PINF)
     1/((2.0*PAMB)-PPL))**.2862241256D0))
      CML(J)=(FLOL*VJL)/(Q*4.332271417D0)
C
C     LINE OUTPUT
C
      WRITE (6,40)
      WRITE (6,55) F(J)
      WRITE (6,20)
      WRITE (6,25) Q,VEL,PERCEN,OMEGA(J),CMU(J),
     1VJU,FLOU,CML(J),VJL,FLOL
      WRITE (6,30)
      DO 300 I=1,16
      WRITE (6,35) LPOS(I),CP(I,J)
  300 CONTINUE
 1000 CONTINUE
C
C     PLOTTING ROUTINES
C
      NPTS=28
      EXSC=15.0
      YSCL=.006
      MX=0
      MY=0
      CALL DRAW(NPTS,OMEGA,CML,1,1,LABEL1,TITLE1
     1,EXSC,YSCL,0,0,MX,MY,9,15,0,LAST)
      WRITE (6,50) LAST
      CALL DRAW(NPTS,OMEGA,CMU,3,2,LABEL2,TITLE1
     1,EXSC,YSCL,0,0,MX,MY,9,15,0,LAST)
      WRITE (6,50) LAST
      DO 2000 J=1,28
      DO 1100 I=1,16
      K=17-I
      CP1(I)=CP(K,J)
 1100 CONTINUE
      CALL DRAW(16,POSL,CP1,0,2,LABEL3,TITLE2,
     12.0,0.0,0,0,1,0,8,8,0,LAST)
      WRITE (6,50) LAST
 2000 CONTINUE
      STOP
      END
```

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